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Monitoring drill performance by means of acoustic emission signal.

Doug Ki. Chang
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MONITORING DRILL PERFORMANCE
BY MEANS OF
ACOUSTIC EMISSION SIGNAL

by

Doug Ki Chang

A Dissertation
Submitted to the Faculty of Graduate Studies and Research
through the Department of Mechanical Engineering in
Partial Fulfilment of the Requirements for the
Degree of Doctor of Philosophy at the
University of Windsor

Windsor, Ontario, Canada

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ABSTRACT

Some parameters for monitoring drill condition during drilling operations are investigated by means of Acoustic Emission (AE) signals. To establish the effectiveness of the AE signal in monitoring drilling operations, the relationships between cutting resistance, strain energy and AE signals are reviewed. The AE signals are acquired during drilling steel plates or steel rods, with different sizes of twist drills on a milling machine or a lathe. The acquired AE signals are analyzed in the time domain and the frequency domain, and the results are compared to directly measured drill wear by means of a travelling microscope. After extensive testing it was found that best results were obtained with the AE count rate, True RMS and with some statistical descriptors. Basic relationships and trends were established for monitoring drill wear and to detect the onset of catastrophic failure. A drill life equation was also developed.

DEDICATION

This work is dedicated to my wife on our fifteenth anniversary.

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NOMENCLATURE

α	= Rake angle,
α_1	= Coefficients of AE count equation
α_3	= Skewness
α_4	= Kurtosis
β_1	= Shear angle of the drill at any diameter d_1
γ	= Shear strain
$\dot{\gamma}$	= Shear strain rate
γ_{oi}	= Effective rake angle corresponding to a drill diameter d_1
γ_{ni}	= Normal rake angle corresponding to a drill diameter d_1
γ_{oi}	= Orthogonal rake angle at any radius of drill
δ	= Clearance angle
ϵ	= Strain
ϵ^p	= Specimen elongation caused by plastic deformation
$\Delta\epsilon^p$	= Plastic strain increment
ζ	= Normalized AE count
ζ_{x1}	= Chip reduction coefficient of drilling
θ	= Helix angle of drill
θ_c	= Clearance angle of drill
ρ	= Dislocation density
ρ	= 1/2 point angle of drill
σ	= Stress
τ	= Shear stress
ϕ	= Shear angle
A	= Cross sectional area

AE = Acoustic emission
 b = Magnitude of Burgers vector
 d = Diameter of drill
 d_c = Diameter of chisel edge
 dV = An element of volume
 dW = Energy increment per unit volume of plastic deformation.
 E = Elastic modulus
 F = Feed
 h = Normalized drill life
 H = Local tangent slope at point P
 K = Stiffness
 L = Tension specimen length
 r_c = t_1/t_2 , cutting ratio
 RMS = Root mean square
 s = Standard deviation
 S = Cross head speed of tension testing machine.
 \bar{S} = Average dislocation velocity
 ΔS = Dislocation of shear plane
 T = Drill life in Taylor's equation
 ΔT = Time interval
 t_1 = Undeformed chip thickness
 t_2 = chip thickness
 TRMS = True root mean square, $TRMS = (RMS)^2$
 UE = Ultra sonic energy
 V = Volume of participating material, mm^3
 V_c = Chip velocity

V_c = Cutting velocity.

w = Web thickness

dW = Energy increment per unit volume of plastic deformation

\dot{W} = Energy dissipation rate over the entire volume of plastic deformation.

CHAPTER 1

INTRODUCTION

Recent developments of technology now make possible the automation of almost every manufacturing process. One of the principal functions of automatic manufacturing is workpiece control and replacement of cutting tools at the right location and at the appropriate level of tool life. This process control should be designed to avoid interference with production and with minimum machine idle time. However, proper cutting tool replacement still remains as one of the most important problems of automated manufacturing because the on-line tool wear and breakage detection techniques are insufficiently developed to be fully effective. Also, tool life management has significant influence on productivity due to either under utilization of tools or the increase of scrap and machine down time. Nearly 50 percent of machine down time is due to direct and indirect tool failure.

The objective of this research is to study several parameters which provide effective monitoring of the condition of the drills during cutting by means of acoustic emission signals, and to determine the basic relationships between these parameters and the developing wear and failure of the tools.

The existing knowledge, which is related to metal cutting, tool monitoring and acoustic emission, was investigated by means of an extensive literature survey. Subsequently the acoustic

emission from drills and materials during torsion and fracture tests was studied. Drilling process was selected for this study since it is one of the most frequent machining operations and the relevant monitoring techniques are not yet well developed. Different machines, different workpiece materials and different sizes of drills were used to simulate the practical manufacturing applications.

Besides turning, drilling is the most frequent machining operations in the manufacturing industry. This is particularly true with drilling, which on average makes up one third of all metal cutting operations. In most manufacturing industries, drill replacement is based on statistically predetermined life. This system can not prevent catastrophic tool failures and increases the cost of tooling because of under utilization. It is estimated that an effective on-line tool monitoring system could save as much as 40% of the machining cost [72].

Tool failure mechanisms have been investigated by many researchers. The general findings are that tool failure may be classified into three main types:

- (1) Progressive tool wear such as flank wear, crater wear, and nose wear due to the basic mechanisms of abrasion, adhesion, diffusion and electrochemical action.
- (2) Sudden premature fracture of the cutting edge because of tool distortion due to bulk plastic deformation.
- (3) Mechanical failure due to fatigue, chipping and misalignment of product line.

The two factors, that have predominant influence in drilling are the drill-bit sharpness and drilling feed rate, which determine the axial, torsional, and bending forces applied to the drill bit and the strength of the dynamic excitation on the drill bit.

Tool wear sensing techniques fall into two general categories: The direct method, which measures tool wear itself, and the indirect method, which measures tool wear by correlation to other parameters such as surface vibration/acoustic emission of the cutting tool, cutting tool temperature, cutting force, etc. However, with the increasing trend in automatically controlled machining systems, the search for on-line tool wear sensing is being intensified because direct wear measurement is difficult to make in-process. Hence, extensive work is now in progress to study relationships between wear rate and other variables, which might provide earlier and more sensitive indications of progressive tool wear.

The monitoring of drill performance involves the detection of gradual wear failure and fracture failure of the drill. According to the literature survey, the indirect detection of tool fracture during cutting is deemed to be more important than sensing of tool wear for the following reasons:

- (1) Tool fracture is a stochastic process and more difficult to predict in comparison with tool wear.
- (2) Tool fracture is apt to cause serious damage to the product and the machine tool.

(3) Confident tool breakage detection systems can increase productivity by allowing the use of more aggressive metal removal rate without fear of machine damages.

Thus, the monitoring of tool failure - both failure due to gradual tool wear or catastrophic failure - with indirect tool monitoring method based on progressive tool wear data, is the most desirable approach.

One of the possible methods of monitoring for this purpose is by means of acoustic emission. It is a very high frequency vibration, which is produced by elastic stress waves generated in a material as a result of a rearrangement of its internal structure. Acoustic emission is thus generated by various mechanisms in a material, including plastic deformation and fracture, which are the major sources of acoustic emission in metal cutting. Research by Iwata [33][34] indicates that the nature of the emission signal is relatively little affected by the location of the sensor or transducer, even though there is some attenuation when it is placed further from the cutting edge. In some applications, this could be the crucial advantage which could overcome the difficulty of installing the sensor or transducer in the rough cutting environments.

Much of the previous research dealt with the application of acoustic emission to on-line tool wear prediction in turning. However, not much work has been done with monitoring of drilling performance. Also, what has been done to date is often criticized in practical applications because of erroneous interpretations.

The most serious problem is the possibility of responding to noise and sending alarm signals even when the cutting tools are operating under normal conditions. The problem is how to distinguish the signal during tool wear/breakage from the background noise.

Dunegan [18] claimed that acoustic emission data can be used to avert catastrophic failure of any structure. For the reliable applications of this method the acoustic emissions from normal operation and the failure process have to be clearly established.

Amplitude changes with the accumulated drilling time (or number of drilled holes) were investigated in terms of count rate and TRMS, and the resulting frequency spectra were analyzed to relate the AE signal characteristics with the drill life. Statistical parameters, such as mean, standard deviation, RMS, skew and kurtosis of the time-amplitude signals, were also studied. A mathematical model was developed from the combination of an existing tool life equation and acquired experimental results. A data processing program, for the whole procedure from the acquisition of drilling data to plotting the results, was also developed for use with an IBM PC-Computer.

CHAPTER 2

LITERATURE SURVEY

Various methods of tool condition monitoring techniques cited in published literature are discussed in this chapter.

Because of the frequencies of failure and the related manufacturing interruptions which were investigated by Kegg [42], cutting tool condition monitoring during machining is one of the most important aspects of productivity. From Table 2.1, as reported by Weck [88], it can be seen that nearly 50 percent of machine downtime is due to direct and indirect tool failure. Additional losses are caused by damage and lost production resulting from catastrophic tool failures.

Part handling system	20.1%
DNC	18.2%
Tool changer	14.6%
Tool length setting	14.1%
Machine	12.1%
Miscellaneous	7.0%
Cutting tool failure	6.8%
Workpiece holding	2.6%
Buffer control	1.7%
Coolant problems	1.7%
Pallet clamping	1.1%
Chip problem	0.9%

Table 2.1. Causes of machining center downtime [42].

In this chapter, four sections of previous publications relating to monitoring of cutting tools are reviewed as follows:

- 1) existing tool condition monitoring systems;
- 2) the characteristics of drilling performance;
- 3) the characteristics of acoustic emission and its applications;
- 4) previous researches of tool condition monitoring with the use of acoustic emission signals.

2.1. Cutting Tool Condition Monitoring

Lister [50] divided his survey on tool condition monitoring into two large categories, the direct and indirect procedures, for the monitoring of tool conditions. He defined the direct method as taking measurements associated with the volumetric loss of the cutting tool material. This is an 'off-line' technique, since the measurement can usually only be taken when the tool is out of cut. Indirect methods, however, utilize measurements of cutting parameters, e.g. forces, which may be correlated with the extent of tool wear, and as a result are generally considered as being 'on-line' techniques. The tool monitoring techniques, which were reported by Lister [50], Blum [5] and Shiraishi [76], and some additional and more recent techniques are summarized in Figure 2.1.

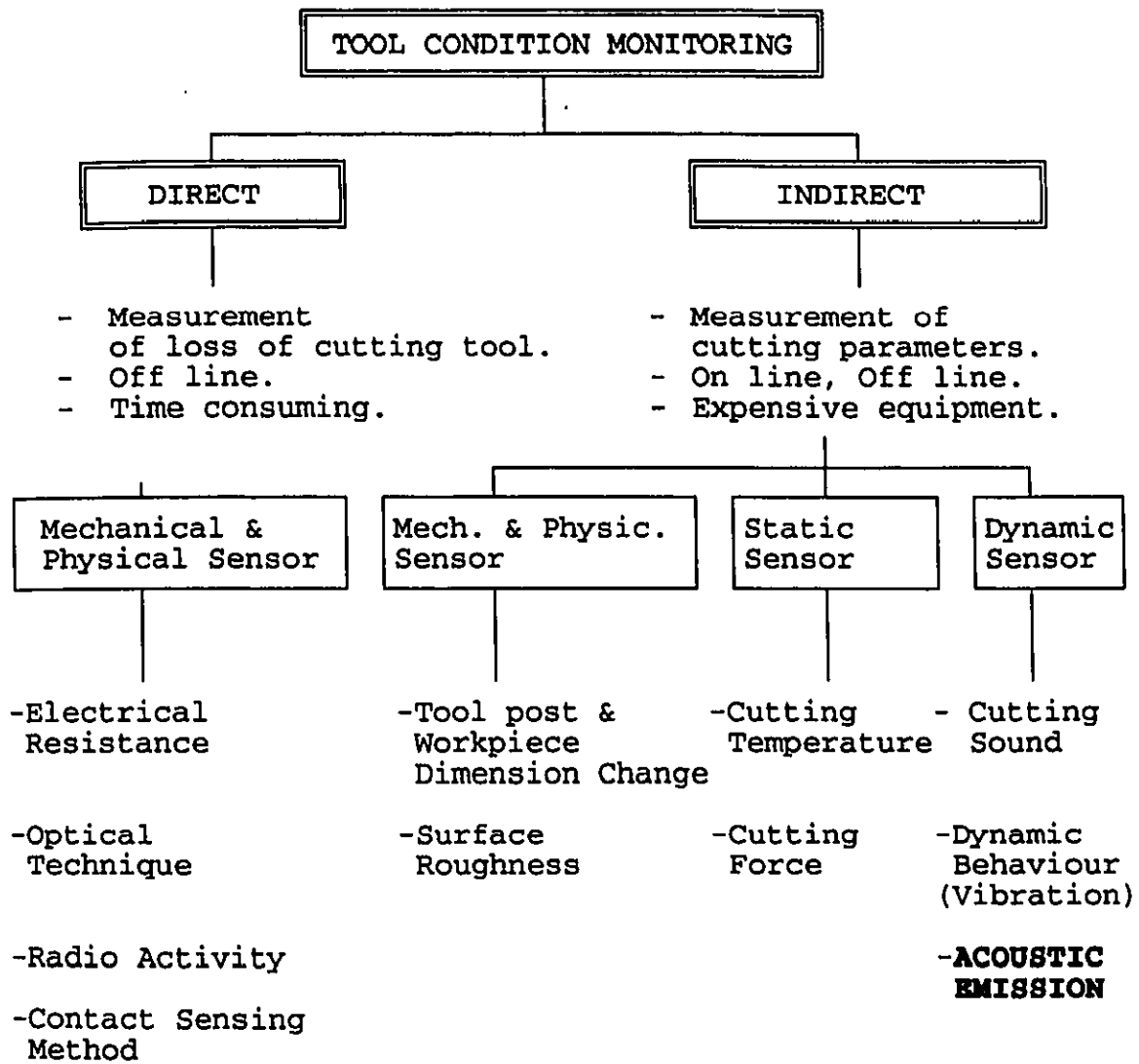


Figure 2.1. Summary of tool condition monitoring systems.

2.1.1. Direct Methods

The direct methods, which measure the tool directly and evaluate the volumetric losses from the tool due to wear are:

- a) the electrical resistance methods,
- b) optical methods,
- c) radioactive sensing methods,
- d) contact sensing methods.

2.1.1.1. Electrical Resistance Methods

The electrical resistance methods which are based upon the fact that the electrical resistance across the tool/work junction would decrease as the area of contact, due to flank wear is increased, was developed by Wilkinson [90] and many other researchers. In this method, the electrical printed circuit or resistor was mounted on to the clearance surface of the cutting tool and then the resistance was detected by passing a known contact current through the interface and measuring the potential difference across it. However, Shiraishi [76] reported that this method has a low resolution of about 20 μm in the area of wear and is not consistent because the resistance easily changes with the temperature and intermittent cutting operations generate cyclic temperature changes.

2.1.1.2. Optical Methods

Early methods of optical tool wear measurements involved the interruption of the machining process at intervals, removal of the tool, and determination of the wear under an optical microscope. Since then optical electronic sensors were eventually developed which eliminate the tool removal although the machining process is still interrupted.

Frost-Smith et al [23] used a magnified image of the wear land on an optical slit. The cathode of a photo multiplier behind the slit generated the signal proportional to the tool wear. Giusti and et al [25] placed the fibre optic sensors close to the flank face of the cutting tool. By setting the desired maximum land width on the instrument a signal is generated when the preset value is reached.

In more recent optical tool-wear sensing techniques, an adequate amount of light is projected onto the tool edge and the characteristics of the reflected light, which depend on the surface wear of the tool, are analyzed. These methods rely upon the higher reflective properties of the wear land compared with the unworn surface [91]. In the reflection pattern methods [65][60], an optical Fourier Transform technique has recently been developed to measure the properties of the grinding wheel surface using a power spectrum pattern. The proposed method is considered as one of the promising techniques among the optical methods and is now under investigation for its practical use.

Matsushima et al [55] used a T.V. camera to monitor tool wear as an inter-process technique in turning. The image of the tool wear is displayed on a TV screen and analyzed by a computer using pattern recognition techniques. However, the proposed system is evaluated as rather expensive, does not have high accuracy and cannot be applied as an in-process technique [76].

A similar technique to measure the flank wear was used in recent research by Rutelli [74] and Liu [51]. Rutelli used an analog T.V. camera to capture the tool wear land image while Liu used a Charge Coupled Device (CCD) camera. They digitized and processed the captured image using a computer system. Liu digitized the image of the entire drill point using 64 grey levels and determined the threshold level which represents the drill wear. After the threshold value was determined, all pixels that had a luminance higher than the threshold were displayed and treated as the worn area. Summary of the above techniques, however, considerable efforts will be required with respect to reliability in the hostile cutting environment because the attenuation and scatter of light is very sensitive in capturing the image.

2.1.1.3. Radio-Active Techniques

In the early testing stages of this technique, the entire tool was made radioactive by irradiating it in a nuclear reactor and the wear of the tool was estimated from the radioactivity of

the material worn off.

Amini [1] made a very small region of the tool close to the cutting edge radioactive by exposing it to a beam of charged particles from a cyclotron. The radioactivity of the tool decreases by a significant fraction during the wear test, so wear was related to the decrease of this activity.

An advanced method has been introduced by sensing the presence of a micro-isotope implanted in the tool flank at a known distance from the cutting edge [7]. After each cutting cycle, the tool's activity is measured for a short time by the Geiger counter. A similar technique has been applied recently to detect drill wear by an in-process measurement. The method basically consists of irradiating an area adjacent to the cutting edge of the tool with a beam of high energy particles [35]. The interaction of particles with tool material causes nuclear reactions, resulting in the formation of radionuclides in the surface layers. The gamma ray emission is monitored directly from the tool with a scintillation detector, and the tool wear is calculated by measuring the residual activity in the tool [76].

These procedures have, however, potential or perceived occupational health hazards and are therefore unlikely to be used on production lines.

2.1.1.4. Contact Sensing Methods

In contact sensing methods the tool dimensions are measured

by direct contact of the cutting tool with a touch trigger probe which basically consists of a displacement transducer and a stylus. As an example, the wear or chipping of milling cutter teeth can be detected by simply contacting the stylus with the rotating cutter. Recently, Suzuki [80] developed a commercially available linear displacement eddy current type transducer which improves the previous electric micrometer method. However, its use in on-line tool monitoring is clearly limited because of the direct contact between stylus and workpiece surface.

2.1.2. Indirect Methods

The indirect methods, which measure tool wear by correlation with other parameters, are:

- a) measurement of the gap between tool and workpiece,
- b) measurement of machined surface roughness,
- c) measurement of cutting temperature,
- d) measurement of cutting forces and associated parameters,
- e) measurement of the dynamic behaviour in terms of sound and vibration, and
- f) measurement of Acoustic Emission signal.

2.1.2.1. Measurement of the gap between the tool and workpiece

In this method, the cutting tool wear is determined by the change in the distance between the machined surface and some

point on the tool flank or the tool holder.

General Electric Corporate Research and Development group [35] are reported to have developed a fluidic measuring system which can measure tool wear up to 0.4 mm with a sensitivity of the order of 2-3 μm .

In the electric micrometer method, which is proposed by Takeyama [83], a feeler from the primary detector is in contact with the work surface in turning immediately after being machined by the side cutting edge of the tool. With the progress of flank wear, the feeler drifts toward the tool axis, thus generating an electrical output proportional to the area of wear. A compensating detector, close to the tool edge, is also provided to remove the error caused by the cutting temperature and cutting force.

Suzuki and Weinmann [80] have developed a wear sensor by using an eddy current transducer and a tungsten carbide stylus. In this method, a tungsten stylus which projects from sensor is in contact with the workpiece. The stylus moves with the wear of the cutting tool and the proximity probe in the sensor generates a signal proportional to the displacement. This method is applicable to straight turning with an accuracy of about 5 μm and is promising among the gap detection techniques.

A pneumatic proximity gauge was also used to detect the distance between tool post and work surface. In this method, two nozzles, one pilot nozzle and the other measurement nozzle, were installed in the cutting tool and the air pressure from the pilot nozzle to the measurement nozzle was analyzed. In the early stage

of this work the nozzles were installed within the cutting tool and that produced poor machinability [2]. In a more recently developed system, a nozzle is just below the cutting edge [35], or within the tool holder so that the nozzle is not subject to wear [79]. The pressurized air ensures that the work surface remains clear under flood cooling conditions.

A prototype ultrasonic micrometer using the transit time of successive pulses has been developed, which gives an accurate and continuous read-out of tool wear [56][57]. The ultrasonic pulses strike the workpiece and then are reflected from its surface. The transit time gradually decreases with the progress of tool wear.

An optical micrometer, mounted on the tool post, consists of a HeNe gas laser, an optical lens and a photo detector [35]. A laser spot on the work surface is located 0.4 mm below the tool edge. This spot is magnified optically, keeping its angle of view at 10° . The reflection of this spot is received by a photo detector fixed to the tool post. Thus the measurement is made by sensing the movement of the optical image on the detector in accordance with the progress of the tool wear. In this method, inaccuracy of the tool holder path, temperature variations of the work surface and high potential of damage by cooling fluid and chips still remain as unsolved problems.

2.1.2.2. Measurement of cutting temperature

The wear rate is dependent on cutting temperature [83]. Three methods have been proposed for this measurement. They are:

- 1) Thermocouples,
- 2) Thermo electromotive force,
- 3) Infra-red emissions.

Thermocouples are often used to measure temperature. They are normally embedded in the tool tip near the cutting edge and the thermocouple voltage is measured during machining. This method has an advantage that the tool can be a sensing device itself. However, Hinds [29] observed that it is extremely difficult to determine accurately the wear rate from thermocouple voltage for the following reasons:

- (a) There are various modes of wear and many modes of failure for a given tool edge can proceed to failure in many ways.
- (b) The noise and bias are different when measuring with different tool edges.

Thermal emf(electromotive force) at the tool/work junction rather than the temperature was taken as the independent variable, to measure tool wear. However, Billette [4] observed there are also practical difficulties due to the following drawbacks:

- (a) the measurements are greatly influenced by the material properties, and therefore, calibration at each cutting is required,

- (b) the signals obtained are rather noisy due to chip curls,
- (c) for the effective measurement of thermal emf, an insulated tool or workpiece is essential.

The infra-red method is a non-contact procedure which detects the average temperature near the cutting area by the infra-red radiation from the cutting surface [85]. The measuring system provides a high response and sensitivity. However, difficulties occur in the focusing onto the area of interest and the inability of using this method in the presence of cutting fluids.

Lister [50] concluded that, tool condition monitoring by temperature measurement is not practical, unless it is used to control the cutting temperature, thereby achieving a 'constant' tool wear rate.

2.1.2.3. Measurement of cutting force and associated parameters

One of the more effective parameters to determine tool wear is the cutting force, which can be measured by a dynamometer or a spindle torque sensor. In the early stages of tool monitoring research, Micheletti [56][57][58] found a relation between tool wear and cutting force in steel turning. His tests show that while the wear land produces an increase of the main cutting force and of the feed force, cratering produces a decrease in the cutting forces, roughly compensating the other effects. However, in these tests the tool wear was obtained artificially by suitable grinding instead of gradual wear due to repeated turning. Both

the flank wear and the crater wear of the cutting tools in NC machining were detected through the examination of the form of the feed force oscillogram by Uehara [86] in 1970's. Since then, research has continued to improve the use of the cutting force as a parameter of tool wear.

A mathematical formula was established by Sewailem [75] to relate the incremental force to the applied force and the maximum depth of nose wear.

In a commercially available system, the thrust force of the spindle of a lathe is measured with a sensor which is built-in into a spindle bearing [84]. The sensor is completely enclosed in a vacuum chamber to avoid the effects of, for example, the coolant or lubricant.

Trusty [84] summarized various ways of measuring the cutting force with various types of dynamometers as follows:

- a) tool holder dynamometer on lathes;
- b) table type dynamometer on milling and drilling machines;
- c) dynamometer built into the spindle bearings;
- d) evaluating the cutting force from the spindle motor current, voltage and speed [43][44].

Recent research has concentrated on multiple sensory signal techniques which process more than one set of information from machining to provide a correlation between tool wear and a spectrum peak, or the amplitude of the dynamic components of the cutting force. The tool wear is indirectly sensed by monitoring the peak value in the power spectrum and compared to the wear

which is measured by a direct method. The sensors used for these measurements are a dynamometer, a load cell transducer, or a thrust force sensor. Owing to the ease of use, these techniques are promising. However, Lister [50] reported, as the limitation of this method, that the input resulting from any one of the above events is indiscriminate of the cause. It is not possible to separate the force increment due to tool wear, with the possible exception of a catastrophic tool failure, from the increments due to other occurrences. To make these technique feasible, large amount of data should be processed under different machining conditions with a combinations of variety of tool, workpiece material and tool geometries, to establish the basic relations.

2.1.2.4. Measurement of machining sound

In this approach, cutting sounds are acquired from a microphone and are then analyzed with various signal processing techniques in the time and frequency domains. Yamazaki et al [91] performed a frequency analysis of the cutting sound and Braun et al [6] investigated the relationship between drill life, the sound, and drift forces produced by drilling process. However, interference and masking by noise emitted from adjacent machines and damage to the microphone in the hostile cutting environment are the main problems in practical applications.

2.1.2.5. Measurement of the dynamic behaviour in terms of vibration

In this approach, vibrations during cuttings are acquired from a transducer and are then analyzed with various signal processing techniques in the time and frequency domains.

Raghunandan et al [71] stated that vibration signal analysis is attractive because of the ruggedness of the sensors and the ease of measurement and analysis.

A piezo-electric type accelerometer is generally used as the sensing device because of its small size, resistance to damage and low cost.

The vibration signals are normally analyzed with time, frequency and amplitude techniques. Table 2.2 shows some examples of tool monitoring by means of vibration.

Year	Author	Machining	Freq. kHz	Data Processing Parameters
1969	Weller[89]	Turning	4 - 6	Total Power Content
1976	Martin[53]	Turning	2 - 3	Power Spectra
1976	Taglia[81]	Turning	2 - 3	Power Spectra
1982	Pandit[68] [69]	Turning	0 - 30	Data Dependent System
1982	Yee, Blom- quist[92]	Drilling	*1	Time Domain Analysis
1983	Shumsheru- ddin[77]	Turning	0 - 6	Power Spectra
1986	Pearce[70]	Milling	0 - 1	Cepstrum Analysis
1987	Lau[47]	Drilling	0 - 10	Statistical Analysis
1988	Okafor Chyou[66]	Milling	*2	RMS vs. No. of Cut
1990	Reif Moore[73]	Drilling Milling	0 - 20	Accel. vs. Wear Statistical Analysis Power Spectra
1990	Taibi Penny[82]	Turning	0 - 25	Power Spectra

- *1. a resonance of 18.2 kHz accelerometer.
 *2. a resonance of 42 kHz accelerometer.

Table 2.2. Tool monitoring progress based on vibration.

Weller [89] measured the total power content in the frequency range of 4 to 8 kHz to relate machining variables, e.g., speed and feed, to wear in turning operation.

The vertical vibrations of a lathe have been measured in terms of their amplitude to find a tool wear limit. Similar research was carried out by Taglia [81] in a different frequency range. The frequencies were divided into discrete bands and were

analyzed to obtain a relationship between tool wear and power spectra.

Shumsheruddin [77] measured the vibration of the cutter during milling and the result showed that the power spectral density is related to the tool wear. In these experiments, the vibration measuring accelerometer was held in contact with the shrunk fitted ring on the milling cutter by means of the leaf springs. However, the power spectra in his results were only related to spindle speed, width and depth of cut rather than gradual tool wear.

Okafor [66] measured the energy content of a vibration signal in terms of RMS values, and plotted against number of cuts. He compared the characteristics of the RMS curve to that of RSS (residual sum of squares which was obtained from the measurement of cutting force) curves.

A different data processing method in turning has been introduced by Pandit [68][69] on the basis of the Data Dependent System (DDS) modelling of vibrations from an accelerometer mounted on the tool holder. The DDS provides an estimate of the tool acceleration component, which is sensitive to wear alone, at the natural frequency of the tool confirmed by impulse response testing. This acceleration decreases at the beginning, approaches a minimum at the critical wear, and increases again, much the same way as the rate of wear curve. The technique proposed is unaffected by background noise and tool geometries, and has industrial potential. However, its accuracy depends on the DDS

model order which strictly relates to the filtering technique applied to the signals.

Statistical analysis of vibration signals, such as mean, skewness, kurtosis and amplitude distribution, is also discussed by Lau [47].

Raghunandan [71] concluded, that vibration sensing might be limited in actual usage since the signals are greatly influenced by the surrounding noise such as forced vibrations, chatter vibrations and tool holder dynamics.

2.1.2.6. Sonic Vibration

Hayashi et al [28] proposed the use of ultra sonic energy (UE) for tool breakage signatures. The frequency range in their measurement was 20 kHz to 80 kHz. Hayashi claimed that UE and AE share the same possible emission source and the UE signal is sensitive to the machining conditions, and its sensitivity to depth of cut is exploited to detect tool breakage.

2.1.2.7. Acoustic Emission

Methods based on acoustic emission have promising potential for the detection of tool wear and tool failure. Numerous investigations have been carried out with this method in industrial applications. The theory of acoustic emission and applications of this method to tool monitoring will be discussed in the following sections.

2.2. Theory of Acoustic Emission

According to the literature survey by Green [26], a documented evidence exists in referencing to AE in the 8th century B.C. This was followed by consistently increasing activity from 1923 to 1950 when Kaiser's Ph.D thesis was published in Germany. Since then, the AE technique have been developed from the research results into its application to the industry.

In this section, publications which are deal with the AE signal identification during material testing are reviewed in the beginning, followed by a discussion of conditions during metal cutting operations. Recent applications of AE to monitoring of machine condition are also reviewed and their limitations are discussed.

2.2.1. General Factors of AE Generation

Gills and Hamstad [24] defined acoustic emission as the phenomenon of the generation of low intensity sound waves or elastic waves in solids by straining, and by associated mechanisms such as crack growth or martensitic transformations. Kannatey-Asibu [38][41] defined acoustic emission as the radiation of stress waves by materials in which local dynamic reconstruction of the internal structure occurs with the release of elastic energy and with local plastic flow to relax the internal stresses. Gills and Hamstad [24] described the AE generation phenomenon with the

idealized stress versus strain curve which represents a material being strained slowly and homogeneously under uniaxial stress as follows:

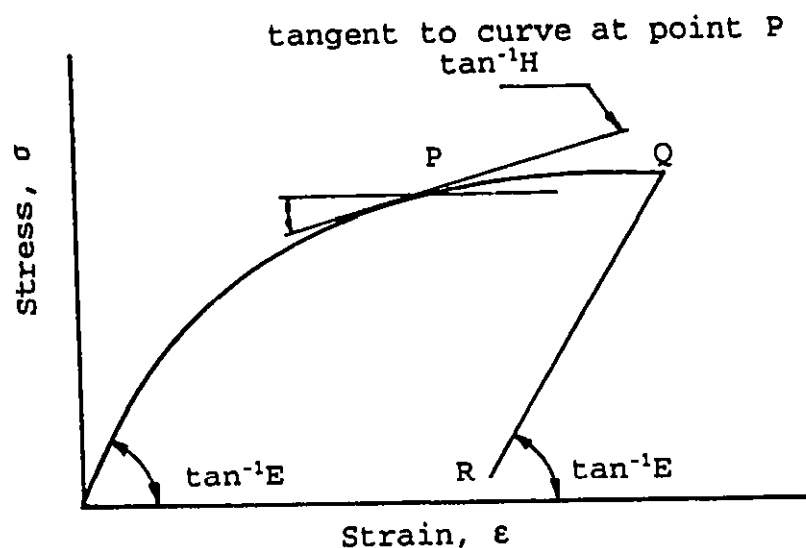


Figure 2.2. Idealized stress vs. strain curve [24].

The initial slope of the curve, as shown in Figure 2.2, is the material characteristic E , the Young's modulus, before the yield point is reached. Past the yield point the slope decreases and is usually a function of strain, but it can be denoted by the local tangent slope H as at point P . Ordinarily $H \ll E$. Also shown in Figure 2.2 is the frequently used idealization that the slope of the curve reverts to the value E during unloading, as line QR . Applying the first law of thermodynamics to this macroscopic structure the authors [24] offered the following

description. For a unit volume of material, the external work required to produce a strain increment $d\epsilon$ is $\sigma d\epsilon$ where σ is the stress. The corresponding increase of flow stress is $Hd\epsilon$, where H is the local tangent modulus. The elastically recoverable strain energy therefore increases from $\sigma^2/2E$ to $(\sigma + Hd\epsilon)^2/2E$, that is, by an amount $(H/E)\sigma d\epsilon$, which is much less than the increment of external work. Treating the unit volume of material as an isolated system, they found, as a result of the first law, that the excess of work over the increase of strain energy, eg. $(1 - H/E)\sigma d\epsilon$, either must increase the internal energy of the system or must be transferred to the surroundings. The authors also interpreted this energy change processes with well established experimental results obtained previously by Farren and Taylor [21]. Most of this energy for plastic deformation can ultimately be accounted for as heat generated in the material. A certain amount of the work of plastic deformation is stored in the micro structural alterations of the material, such as increasing in the content of dislocations and other defects. How the operative processes can be linked with the acoustic emission were investigated by Fisher and Lally [22] and they speculate that small, sharp yield drops in the flow stress, as shown in Figure 2.3, are associated with acoustic emissions. According to Fisher and Lally, and as further expounded by Gillis [24], such events are the result of simultaneous motion of many dislocations to extend a deformation band into a less strained region of the crystal. They reported that the stress relaxation or micro-yield

drop is propagated as a pair of longitudinal elastic stress waves emanating from the less strained region of the crystal and propagating the stress decrement toward the specimen ends. These low-intensity elastic waves are the signals detected as acoustic emissions.

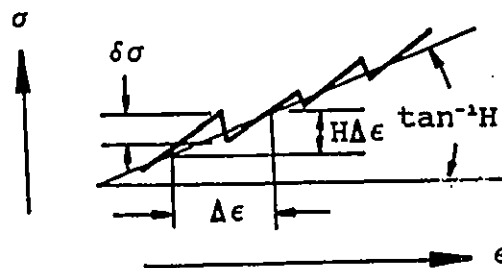


Figure 2.3. Magnified stress vs. strain curve showing micro-yield drops [27].

Kannatey-Ashibu [41] analyzed the AE signal generation during martensitic transformation and concluded that for martensitic transformation, there are changes in volume and shape accompanying the transformation. As a result, there is a substantial amount of energy involved, and that includes: 1) interfacial energy between martensite and matrix, 2) elastic strain energy and 3) plastic

deformation energy. The plastic and elastic energies which constitute a portion of the chemical free energy change are considered the source of AE generation during martensite formation. He also observed that the AE signal generated during martensite formation has a strong dependence on the carbon content, and the value of the RMS signal is dependent on the volume of martensite transformed, and is a function of temperature T , being independent of time for a constant cooling rate.

Two major types of acoustic emission, continuous and burst types, are discussed by Licht [49] and Dunegan [18]. The continuous designation is normally applied to the low level, high signal density emission (Licht expressed this as resembling white noise) observed during tension tests of unflawed specimens. The peak of the acoustic emission is obtained near the yield stress of the material, as shown in Figure 2.4.

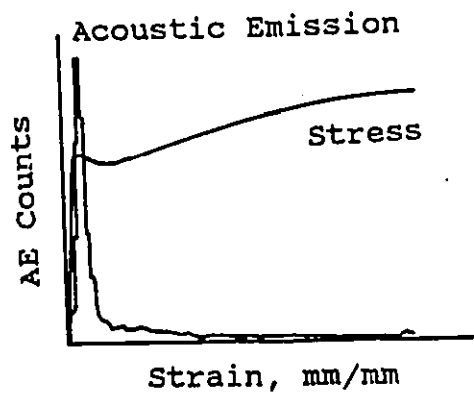


Figure 2.4. Acoustic emission and stress as a function of strain for a mild steel tension specimen [18].

The burst-type emission, with the high amplitude, erratic, low frequency characteristics, was observed prior to yield, but during the early stages of yielding these signals disappeared. Fracture specimens of the same material containing fatigue cracks were tested and yielded primary burst-type emissions as the plastic zone formed at the fatigue crack tip. No continuous-type emission was observed. The presence of burst-type emission, due to the growth of plastic zone at the crack tip, may be explained by the higher effective strain rate in the region near the crack tip and the large stress gradients that occur in this region. However, difficulties were experienced by Licht [49] with a clear distinction between the two types emissions, as there is no logical transition.

Dunegan [18] observed that acoustic emission signals are significantly dependent on materials when stressed. The specific factors, that influence acoustic emission detectability, were summarized as strength, strain rate, anisotropy, nonhomogeneity, structure, phase transformations etc. He claimed that acoustic emission data which are used to avert catastrophic failure of any structure, must be evaluated with reservations. Unless the data is obtained and analyzed under conditions similar to those to which the structure would be exposed and the relationship between acoustic emissions and the failure process has been clearly established, the use of the process is questionable.

2.2.2. Mathematical Theory

Gillis [24], Dunegan [18] and Green [26] provided well established theoretical and experimental results, which shown that the energy contained in an acoustic emission and the rate at which it is dissipated are strongly dependent on the rate of deformation (strain rate), the applied stress, and the volume of the effecting material. Thus, a process can be monitored using acoustic emission if it can be directly related to one or more of the above parameters. Changes in the process parameters can then be correlated with changes in the emission observed. For example, changes in an observed signal of the RMS voltage level and its characteristics can be related to the strain rate and volume.

Gills [24] derived a plastic strain rate equation during a tension test, taking into account machine deflection as well as specimen deformation, as follows:

$$St = \sigma(A/K) + (\sigma/E + \epsilon^p)L. \quad (1)$$

Where t is time from the origin where both stress and strain are zero, σ is the axial stress, σ/E is the axial elastic strain, and ϵ^p is the specimen elongation caused by plastic deformation. Equation (1) was rewritten as:

$$(S/L)t = (\sigma/E)(1 + AE/KL) + \epsilon^p, \quad (2)$$

From Figure 2.3, it can be seen that during a time interval Δt corresponding to the period for one strain jump, the total strain increment, denoted by $\Delta \epsilon$, consists of a net elastic contribution, $\Delta \sigma/E = (H/E)\Delta \epsilon$, plus a plastic increment $\Delta \epsilon^p = (1 - H/E)\Delta \epsilon$. For

the time interval Δt , equation (2) gives:

$$(S/L)\Delta t = [(H/E)(1 + AE/KL) + (1-H/E)]\Delta \epsilon, \quad (3)$$

which can be rewritten to express the average specimen strain rate $\Delta \epsilon / \Delta t$,

$$\epsilon = (S/L) / (1 + AH/KL). \quad (4)$$

The plastic strain rate

$$\epsilon^p = (1-H/E) [(S/L) / (1 + AH/KL)]. \quad (5)$$

In the general case, for an element of volume dV , subject to stresses σ which cause plastic strain increments $d\epsilon^p$, the energy increment per volume dV of plastic deformation (dW) is given by;

$$dW = \sigma d\epsilon_p dV. \quad (6)$$

Over the entire volume, then, the rate of energy dissipation is given by;

$$W = \int_V \sigma \epsilon_p dV. \quad (7)$$

The strain energy in a continuous acoustic emission signal was measured by a true RMS (root-mean-square) voltmeter or a TRMS (true-mean-square) voltmeter. Hamstad [27] found a relatively simple dependence of RMS on the plastic strain rate as well as the volume of the specimen as:

$$\text{RMS} \propto \epsilon_p^{1/2} * V^{1/2}, \quad (8)$$

or

$$\text{TRMS} \propto \epsilon_p * V, \quad (9)$$

where the ϵ_p is the plastic strain rate and V is the volume of the reduced section of the specimen and TRMS defined as square of RMS.

The greatest problem encountered in the application of acoustic emission is the analysis or interpretation of the

emission signals obtained because of the randomness of the acoustic emission process. An emission signal is non-periodic which contains many frequencies and cannot be described by an explicit mathematical relationship. One of the primary methods for quantitatively presenting acoustic emission data is by measuring the energy of the AE signal. The RMS voltage of a continuous AE signal can be used to make this energy measurement.

This method of monitoring the AE signal is known to have several advantages over the traditional count and count rate techniques. Among these are; (a) the smoothing of the acoustic emission data which facilitates the modelling of the data with analytical functions, (b) the disappearance of the extreme sensitivity of the count rate technique to small changes in the threshold level, (c) the reduced sensitivity of the RMS values to small changes in the system electronic gain or in the transducer coupling efficiency, and (d) the possible ease of relating the RMS voltage level of the emission to the energy E contained in the emission. Hamstad [27] expressed the energy of the emission signal as equation (10) from the definition for the RMS voltage in electronics.

$$\Delta E \propto (\text{RMS})^2 \Delta t. \quad (10)$$

when ΔE is the energy expenditure during the interval Δt .

2.3. Acoustic Emission and Metal Cutting

Several possible AE sources during the cutting process were observed by Moriwaki [61][62] and Lan [43][44][45]. They suggest that the possible sources of AE in the metal cutting process are:

- (1) primary deformation (shear) zone,
- (2) secondary deformation (chip-tool interface deformation and friction) zone,
- (3) tertiary deformation (tool flank-work surface) zone,
- (4) chip fracture and contact with the tool or workpiece, and
- (5) tool fracture and chipping.

The AE generated is either continuous (from deformation and friction) or burst (discrete events from chip and tool fracture). However, they emphasized that the principal parameters which affect the acoustic emission from machining are strain rate, applied stress, and the volume involved in the deformation.

Oxley [67] noted in his paper that how complex the geometry of cutting tools (drills, milling cutters, taps, grinding wheels and so on) the material removal processes is basically the same in all cases with a wedge shaped cutting edge (or edges) forming a chip. Because of this, investigations of the machining process, both analytical and experimental, have tended to be concentrated on machining with a single, straight edged cutting tool only as in turning.

Bera and Bhattacharyya [3] also reported that an ordinary twist drill, in spite of its complex geometry, resembles more or

less basic conventional turning. The only difference is the variation of inclination and rake angle, which continuously change inward from the outer nominal radius.

The strain rate from a model of orthogonal cutting was derived, with the assumption of a continuous chip without a built-up edge, by Oxley [67] and Dornfeld [11][13][14] to calculate the cutting force and RMS of the acoustic emission signal, respectively. The schematic model of orthogonal cutting is shown in Figure 2.5; the tool is assumed to be perfectly sharp.

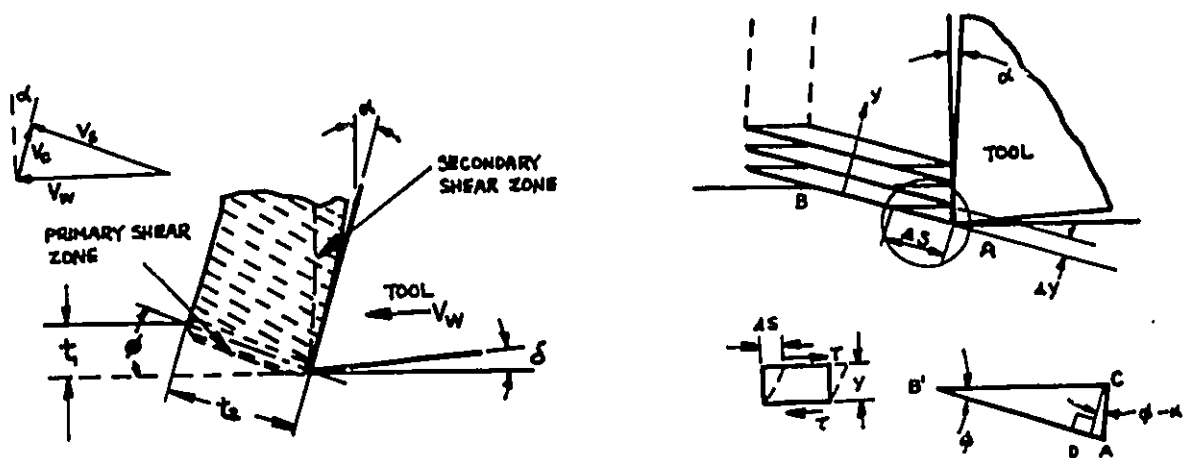


Figure 2.5. Model of chip formation used in analysis [14].

The plane AB, near the center of the chip formation zone, which is found from the same geometric construction as for the shear plane in the shear plane model of chip formation, and the

tool/chip interface are both assumed to be the directions of maximum shear stress and maximum shear strain rate. The basis of the theory is to analyze the stress distributions along AB and the tool/chip interface in terms of the shear angle ϕ (angle made by AB with cutting velocity V_w), work material properties, etc. Once ϕ is known then the chip thickness t_2 and various components of force can be determined from the following geometric relations.

$$t_2 = t_1 \cos(\phi - \alpha) / \sin \phi \quad (11)$$

The shear angle ϕ can be calculated by geometry as

$$\phi = \tan^{-1} \frac{r_c \cos \alpha}{1 - r_c \sin \alpha} \quad (12)$$

where α , rake angle
 δ , clearance angle
 ϕ , shear angle
 V_w , cutting velocity
 V_c , chip velocity
 t_1 , undeformed chip thickness
 t_2 , chip thickness
 $r_c = t_1/t_2$, cutting ratio.

Dornfeld [14] assumed the shear mechanism to act as sliding deck of cards, as illustrated in Figure 2.5, then derived the equation of RMS value during turning in terms of shear strain as follows:

$$\gamma = \Delta s / \Delta y = AD/CD + DB/CD = \tan(\phi - \alpha) + \cos \phi \quad (13)$$

where Δy is the spacing of successive shear planes. Taking into consideration the time ΔT for the metal to move a distance Δs along the shear plane, the shear strain rate during cutting, γ , is

$$\gamma = \Delta s / \Delta y * 1 / \Delta T = V_s / \Delta y \quad (14)$$

where the shear velocity along the shear plane, V_s , is

$$V_s = \{ \cos \alpha / \cos (\phi - \alpha) \} * V_w \quad (15)$$

and from above equations (14) and (15),

$$\gamma = \{ \cos \alpha / \cos (\phi - \alpha) \} * V_w / \Delta y \quad (16)$$

knowing that $r_c = \{ \sin \phi / \cos (\phi - \alpha) \}$ (17)

It is then possible to relate these basic cutting parameters directly to the emission signal characteristics. From equation (16), it is seen that the strain rate is a function of cutting speed. Further, the rate of dislocation generation is a function of the strain rate and the instantaneous dislocation density. The shear strain can be represented as a function of the average distance between dislocations, l ,

$$\gamma = b \rho l \quad (18)$$

where ρ = dislocation density, that is, the number of mobile dislocations in a unit area of the material section, and b is the magnitude of the Burgers vector. Then the strain rate γ is

$$\gamma = d\gamma/dt = b l * (d\rho/dt) + b \rho * (dl/dt) \quad (19)$$

where t is time.

Since dislocation density is defined on a per unit area basis, $\rho = (1/l^2)$, or $l = \rho^{-1/2}$

$$\gamma = 1/2 * b \rho^{-1/2} d\rho/dt \quad (20)$$

or the rate of dislocation generation, ρ , is

$$dp/dt = 2\gamma/b * \rho^{1/2} \quad (21)$$

Here the effects of fixed dislocations and loss of dislocation mobility through interaction are not accounted for. Thus, equation (21) estimates the rate of dislocation generation for a uniform array of mobile dislocations and this rate of generation (and therefore the level of acoustic emission activity) is proportional to the external influenced strain rate in metal cutting.

The average strain rate in metal cutting can also be represented as a function of ρ, b and the average dislocation velocity (21), as

$$\gamma = b\rho\bar{S} \quad (22)$$

where \bar{S} is the average dislocation velocity, and energy rate due to the dislocation generation is given by

$$\dot{E} = \tau_s \gamma_{av} \quad (23)$$

where τ_s is the shear stress in the primary deformation zone. Thus, the energy in the signal over the entire volume of material can be related to material deformation characteristics by equating equation (9) to equation (23) and replacing the stress σ by the shear stress, τ_s , and the strain rate, $\dot{\epsilon}$, by the average shear strain rate, γ_{av} , yielding

$$(RMS)^2 \propto \frac{dE}{dt} = \int_V \tau_s \gamma_{av} dV \quad (24)$$

Then, for material shear strength $k = \tau_s$ and strain rate $\dot{\gamma}$ becomes

$$(RMS)^2 = C_1 k \gamma V \quad (25)$$

where V = volume of participating material.

A comprehensive expression relating the RMS value of the acoustic emission signal to process and material parameters can be written from equations (16) and (25) as;

$$(RMS)^2 = C_1 k \frac{r_c \cos \alpha}{\sin \phi} \frac{V_v}{\Delta y} V \quad (26)$$

or

$$RMS = C_2 \left[k \frac{r_c \cos \alpha}{\sin \alpha} \frac{V_v}{\Delta y} V \right]^{1/2} \quad (27)$$

However, the RMS of the acoustic emission signal was calculated based on the strain rate from a model of orthogonal cutting which was derived with the assumption of a continuous chip without a built-up edge.

2.4. Drilling

The strain rate from a model of orthogonal cutting was derived, with the assumption of a continuous chip without a built-up edge, by Oxley [67] and Dornfeld [14] to calculate the cutting force and RMS of the acoustic emission signal, respectively. The twist drill is a complex tool that usually has two cutting edges designed to produce identical chips. Because of the complexity of

the cutting edge shape, the analysis of the cutting process is more involved than for other tools. The quantities of interest vary with the radial position across the cutting edge. However, Bera[3] reported that a careful determination of the true rake angle at any radial location along the cutting edge make the twist drill resemble more or less a basic conventional turning tool. Hence, the equivalent drill angles of conventional turning tool were surveyed through previous publications to apply the RMS equation for turning operation to drilling operation.

Generally, the most important drill quantities from the analytical point of view are :

- (1) helix angle, θ
- (2) $1/2$ point angle, ϕ
- (3) web thickness, w
- (4) drill diameter, d
- (5) diameter of chisel edge, d_c .

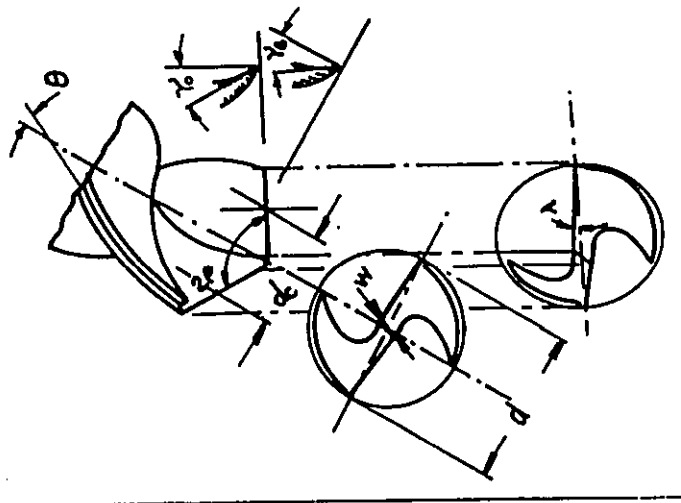


Figure 2.6. Geometry of drill shape at any point on cutting lip.

From the geometry, Bera [3] derived the orthogonal rake angle at any radius corresponding to a diameter d_1 , γ_{o1} , as:

$$\tan \gamma_{o1} = \frac{\frac{d_1}{d_c} \tan \theta - \tan [\sin^{-1} \frac{d_c}{d_1} \sin \rho] \cos \rho}{\sin \rho} \quad (28)$$

where d_c = diameter of chisel edge,
 d_1 = diameter of drill

Further, the normal rake angle corresponding to a diameter d_1 , γ_{n1} , is expressed as:

$$\tan \gamma_{n1} = \tan \gamma_{o1} \cos \lambda_1 \quad (29)$$

$$\lambda_1 = \sin^{-1} (d_c/d_1) \sin \rho \quad (30)$$

where λ_1 = inclination angle at a section corresponding to a diameter d_1 . So, the effective rake angle at that section, γ_{e1} , is

$$\sin \gamma_{e1} = \sin^2 \lambda_1 + \cos^2 \lambda_1 \sin \gamma_{n1} \quad (31)$$

And the shear angle at any location d_1 is described as:

$$\tan \beta_1 = \frac{\cos \gamma_{e1}}{\zeta_{x1} - \sin \gamma_{e1}} \quad (32)$$

where, ζ_{x1} is chip reduction coefficient at any location d_1 .

Since the strain rate is the function of shear angle and chip velocity, we can calculate the RMS value of acoustic emission signals from drilling.

Other distinct characteristics of drill edge, which differ from a conventional turning cutter, were also investigated by

Micheletti [58] on twist drill performance. In his results, there is some evidence of the relative lip height affecting torque, possibly by influencing the efficiency of the cutting process by altering the uncut chip thickness. He also found that the main effect of web offset is similar to that of the relative lip height, in that the depth of cut taken by one lip is increased at the expense of the other one.

2.5. On-Line Tool Monitoring Techniques by means of Acoustic Emission Signals

Iwata and Moriwaki [33][34] glued a piezoelectric transducer on the turning machine tool shank and acquired AE signals within a range of 100 kHz to 400 kHz. They observed a correlation of AE counts, which is the number of times the AE signal exceeds a threshold RMS value, with the RMS value of the signal with respect to the amount of flank wear of the conventional turning cutter. In his results, the RMS voltage increases at first with an increase in the flank wear, and then stays almost constant with further increase in the flank wear. A similar trend with AE counts was obtained although it is less consistent. He suggests that the total AE count is coherent and acceptable as a measure of the flank wear. They also found that the frequency components of AE were concentrated mostly in a range of 100 to 400 kHz, and the AE count is almost negligible when the flank wear is below 120 μm .

Dornfeld [14][16][17] developed an analytical relationship between the acoustic emission generated during machining, based

upon fundamental machining parameters, and he experimentally evaluated the RMS of AE signal versus strain rate, which were obtained both theoretically and experimentally.

Extended research by Kannatey-Ashibu, Jr. and Dornfeld [38] developed a theoretical relationship between the AE and the orthogonal metal cutting parameters by relating the energy content of the AE signal to the plastic work of deformation which generates the emission signals. They expressed the RMS value of the emission in terms of the basic cutting parameters.

Inasaki et al [31][32][33] carried out in-process detection of the cutting tool fracture while most of the previous research monitored AE signals to identify the state of the cutting tool edge. He observed proportional amplitude increase of AE signals to increasing cutter wear when the AE signals were acquired within the frequency range of 100 kHz to 1 MHz. However, no significant change was observed when the AE signal was acquired in the frequency range of 300 kHz to 1 MHz. In the results of AE count versus total machining time, stepwise AE count increase was observed in his results at the tool fracture.

Similar attempts of monitoring of gradual wear and the fracture of the cutting edge were carried out by Dornfeld [11]. Statistical parameters, skew, kurtosis etc., were successfully used in their AE signal analysis. Frequency analysis of AE signals was also used. In their results, stable machining was characterized primarily as low frequency (100K-300K Hz) and lower amplitude signals. Transition to chatter and the initial chatter

was characterized as increasing levels of low and middle frequency activity and higher frequency (600K-800K Hz) activity.

A statistical analysis of the RMS acoustic emission signal from metal cutting was also accomplished by Kannatey-Asibu [40]. The analysis shows that the skew and kurtosis of an assumed β distribution for the RMS acoustic emission signal are sensitive to both the stick-slip transition for chip contact along the tool rake face and progressive tool wear on the flank of the cutting tool.

Miwa et al [58] found that the magnitude of the averaged AE proportionally increases with the amount of the flank wear in turning operations. Kakino et. al [36] found a significant increase in AE power when tool breakage occurred. Later these results were confirmed by Dornfeld and many others [16][17].

Most of the previous studies dealt with turning operations which use single point tools because of the difficulty arising from multi cutting edges due to their complexity.

Application of AE signal monitoring during drilling was observed in Moriwaki's [62] research in 1983. The burst type AE signal is sensed at the time of drill breakage. However, no observations were made with gradual drill wear.

An in-process sensor for detecting drill breakage was developed by Inasaki [31]. The characteristics of AE signals, e.g., signals due to different drill sizes, friction, mechanical noise and electric noise, were observed by the discrimination of AE signals by power ratio (RMS of particular bandwidth versus RMS

of overall measured frequency range). In respect of monitoring of tool breakage the following conclusions were reached:

- (1) The tool breakage signal is hardly affected by the diameter of the drill.
- (2) The acoustic emission signal detected is not too sensitive to the distance between the AE source and the sensor.

However, the analyzed signals were all simulated manually (i.e., drill fracture by impact) instead of actual drilling.

Diel et al [9][10] applied acoustic emission signal analysis to on-line sensing of tool wear in face milling. In his results, both acoustic emission and cutting forces have parameters that correlate closely with flank wear.

Recently, different approaches to analysis of acoustic emission signals have been developed. Emel [19][20] developed a pattern recognition system to identify the source components during turning operations. He also obtained the variable effects on acoustic emission power in terms of wear, speed, feed, workpiece hardness and depth of cut with the use of pattern recognition base identification.

Another approach of machine tool condition monitoring system by means of pattern recognition was carried out by Marks et al [52].

Matsumoto [54] used a linear extrapolation between the flank wear during turning operations and RMS values of the AE signals, and made a model for the RMS value in terms of tool wear.

Another signal processing scheme was developed by Liang [48]. In his study, autoregressive (AR) time-series modelling of the acoustic emission RMS signal has been implemented under a series of experimental conditions. A strong correlation between the tool wear and the values of model parameters was observed in his results.

2.6. Summary

Monitoring methods developed by previous researchers of tool wear and tool failure were reviewed. The monitoring of tool condition is particularly crucial in automated manufacturing processes because it is directly related to the damage of work pieces and the increase of production down time.

At present, the force or torque detection is the most often used method for tool wear sensing. However, the AE method has sufficient industrial potential for the detection of tool failure because it has the following advantages:

- 1) Acoustic emission signals are generated by the processes in the cutting zone, including the chip-tool interface. These have a direct influence on tool wear and can therefore be directly related to processes in these zones.
- 2) The acoustic emission signal is sensitive to the prevailing cutting conditions, tool fractures, and internal cracking which occurs prior to tool fracture.

- 3) There is satisfactory correlation between the AE and the extent of tool wear at any given time.
- 4) The signal is not very sensitive to the distance between the AE source and the sensor.
- 5) The frequency content of the signal is well beyond the frequency range of noise from the machine tool operation and extraneous sources.
- 6) It is easily adapted to computer control.

However, previous studies dealt predominantly with turning operations which use single-point tools. In the case of drilling operations, the difficulties arise from the complex cutting edges and unsymmetry of the chisel edge. Therefore, further studies are required to develop reliable on-line drill condition monitoring techniques.

CHAPTER 3

EXPERIMENTAL DETAILS

The experimental setup and procedure for the acquisition and analysis of the acoustic emission data from drilling are described in this chapter. Two simple experiments, torsion test of an aluminum bar and fracture test of small diameter drills were carried out to observe the characteristics of the acoustic emission signals from the material. Subsequently, experiments to monitor acoustic emission signals during drilling were also carried out.

Figure 3.1 shows the experimental set-up, and Figure 3.2 the schematic diagram of the experiments which were employed in this study. The acoustic emission signals from the source (either workpiece or tool side) were picked up via an electronic transducer and then filtered to the desired frequency range. These signals were processed by means of a digital oscilloscope, True RMS meter, FFT analyzer and AE counter and the results were saved to the personal computer. The signals during the drilling were monitored with the oscilloscope. The drill wear was measured after every drilling operation with the use of a tool microscope. The drilling process and the materials used are only briefly discussed in this chapter, since they are extensively described in standard reference materials on metal cutting.

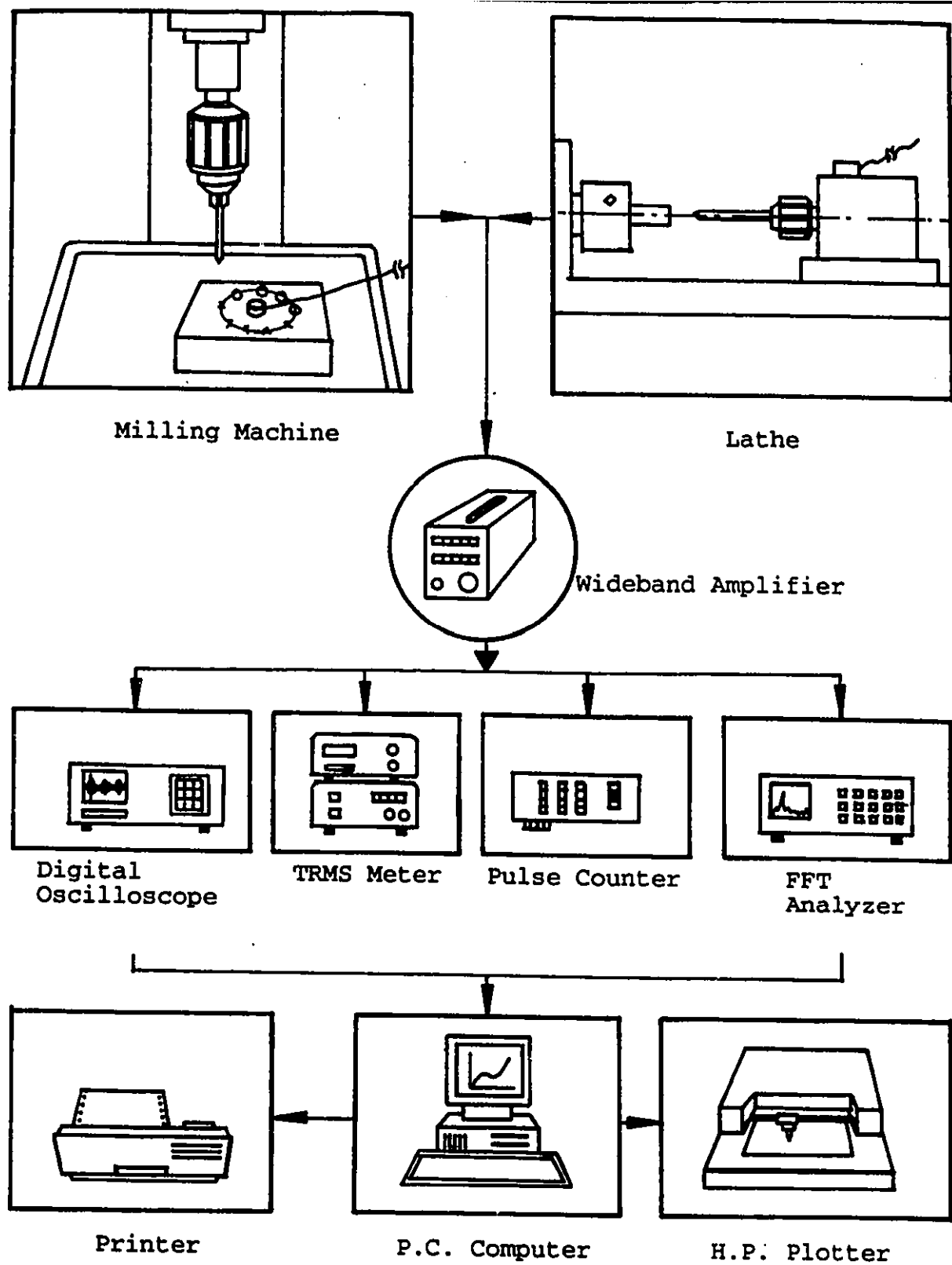


Figure 3.1. Experimental set-up.

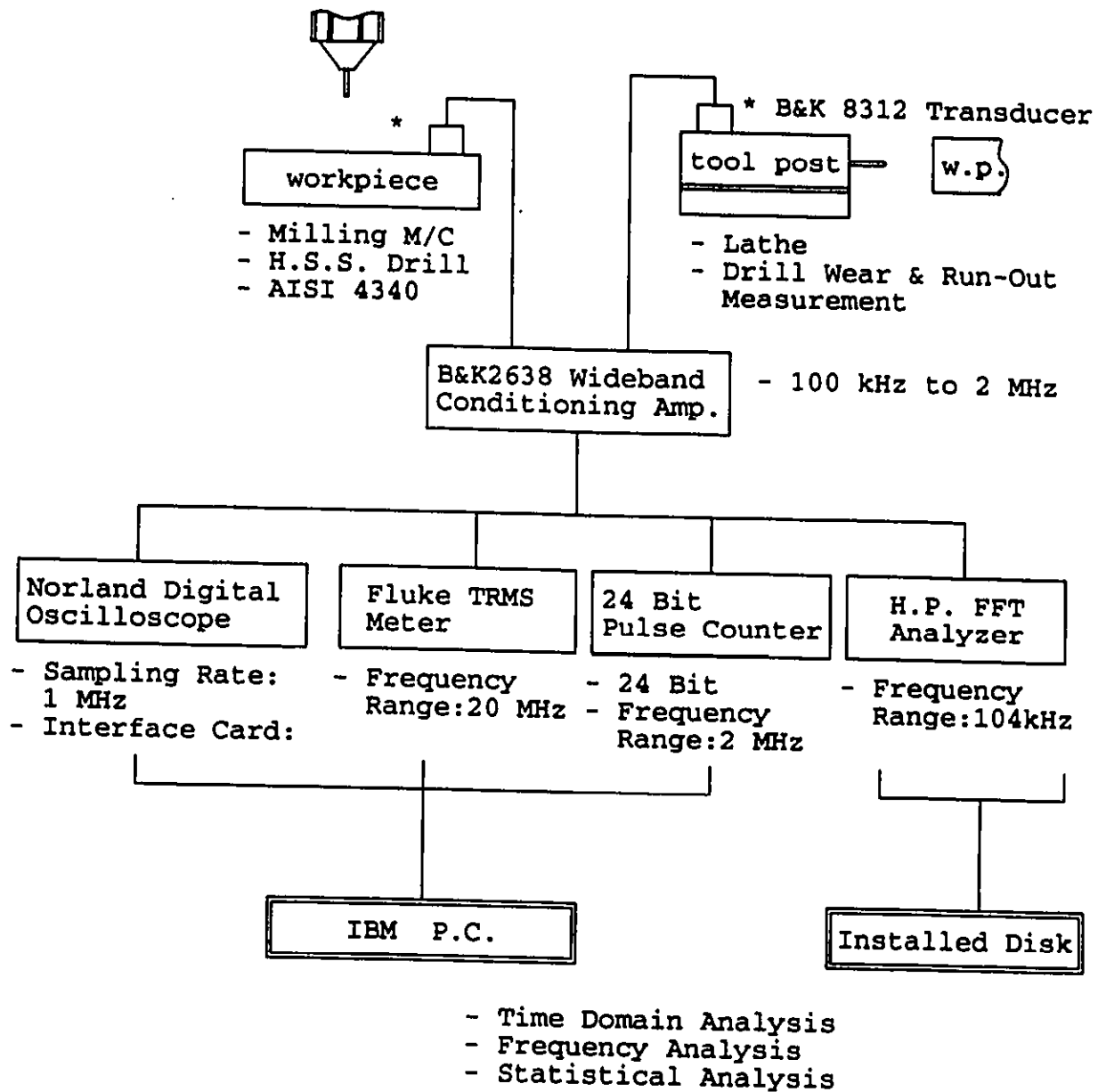


Figure 3.2. Schematic block diagram of experiments

3.1. Torsion Test

The literature survey has already indicated that the energy contained in an acoustic emission is dependent on the strain rate.

To observe the general relations between the RMS of acoustic emission signals and strain, a simple torque test was carried out. As shown in Figure 3.3, different magnitudes of torque were applied to the aluminum bar with the use of a torque wrench. The acoustic emission signals and shear strains were measured by a Digital Oscilloscope (Norland Digital Oscilloscope with B&k 8312 transducer) and a Strain Indicator (Vishay P-350A), respectively.

Digital Oscilloscope

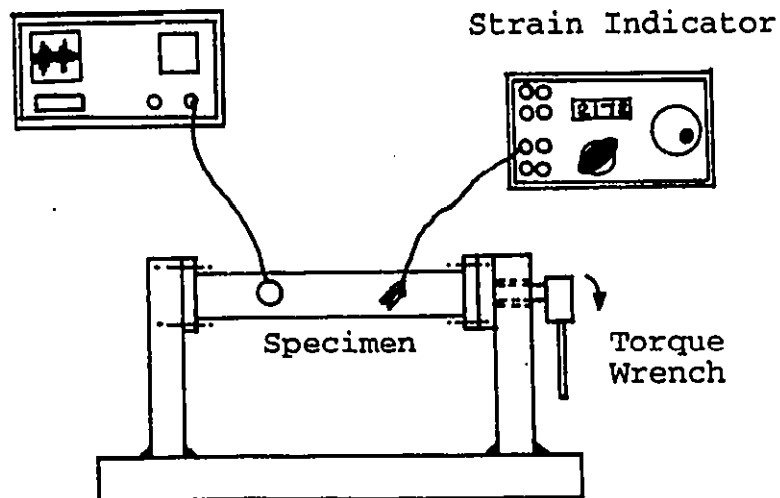


Figure 3.3. Schematics of torsion test.

3.2. Drill Fracture Test

A small size drill ($3/32"$ dia, $1/8"$ dia.) was clamped in the vice and a B&K 8312 transducer was attached on the drill shank to carry out two types of tests, as shown in Figure 3.4. First, a slight impact was given to the drill edge and the signals were captured by digital oscilloscope through the transducer. The tests were repeated with the change of the impact location and direction (e.g., vice, table, horizontal and vertical impact to the drill edge). The captured signals were analyzed by means of a frequency analyzer to observe the frequency characteristics of the drill. Subsequently, the clamped drill was fractured with a impulsive load and the signals were captured through the transducer. The tests were repeated for different sizes of drills. The captured signals were analyzed and plotted as amplitude distributions versus frequency, to observe the predominant frequency band during drill fracture.

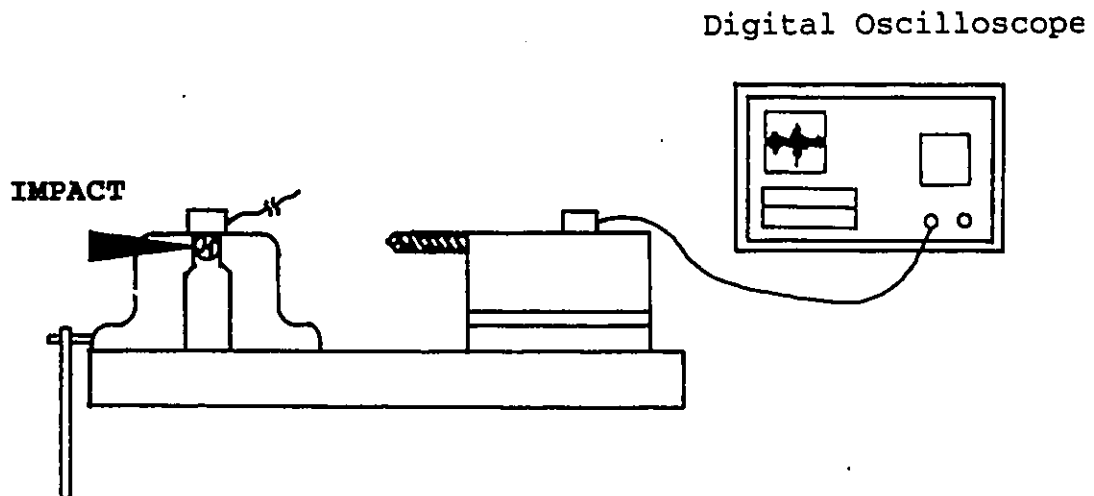


Figure 3.4. Sketch of drill fracture test.

3.3. Machine Tool and Workpiece

Two major machining operations were employed with: a) drill fixed, workpiece rotating and b) drill rotating and workpiece fixed. The acoustic emission data were always captured from the fixed side.

Three general lathes (Harrison M400, Colchester Master 2500, and Okuma type LS) and one vertical milling machine (Bridgeport) were employed to provide the required drilling conditions. With the lathes, the workpiece was rotated and the drill was fixed while the workpiece was fixed and the drill was rotated with the milling machine.

Although Iwata[51] and Kannatey-Asibu[58] found the emission signal unaffected by the location of the transducer, efforts were made to locate the transducer at the same distance from the drilling holes to minimize the error. For the drilling of a square plate with the vertical milling machine, the workpiece was laid-out with the use of a computerized lay-out function in the milling machine and center drilled on the same radius of circle. The transducer was located in the center of the circle to avoid the signal attenuation due to the differing distances between cutting hole and transducer. The material used for drilling and their chemical properties are shown in Table 3.1.

Chemical Property	AISI 4340
Carbon, CO	0.38 - 0.43 %
Manganese, Mn	0.60 - 0.80 %
Phosphorus, P	0.035 %
Sulphur, S	0.04 %
Silicon, Si	0.2 - 0.35 %
Nickel, Ni	1.65 - 2.0 %
Chromium, Cr	0.7 - 0.9 %
Molybdenum, Mo	0.2 - 0.3 %
Brinell Hardness	207 (Rc16)

Table 3.1. Typical analysis of workpiece.

Two different sizes of drills were employed. For each combination of drill and specimens, proper machining speed and feed were selected based on the cutting theory which is described in the general machinery handbook. Table 3.2. shows the specification of drills and drilling conditions.

Drill Size, inches	Drill Material	Workpiece Hardness (Rockwell)	Peripheral Speed (R.P.M.)	Feed Rate (inch/rev.)
1/8"	H.S.S	H Rc 16	175 - 225	0.002
3/16"	H.S.S	H Rc 16	175 - 225	0.035

1. Point angles of the drills are all the same, 118°.
2. Helix angles of the drills are all the same, 25-35°.
3. $V = 0.00314 * D * R.P.M.$
4. $R.P.M. = (318.31 * V)/D$
5. The peripheral speed for the Hb175 - 225 is 50 - 60 SFM.

Table 3.2. Specifications of the cutting tool and machining conditions.

3.4. Transducer and Wideband Conditioning Amplifier

According to the previous researches, most of the AE signal from the metal cutting tests have been detected in the very high and wide frequency ranges. However, the mechanically generated vibration, which occurs in the frequency range of well below 100 kHz, can interfere with the AE measurements, and above 1 MHz structural damping usually results in an unacceptable degree of signal attenuation. The B&K type 8312 piezoelectric transducer was selected to capture the AE signal from the AE sources since it offers high sensitivity over the frequency range 100 kHz to 1 MHz. It has a built-in 40dB preamplifier. The resonance frequency of this transducer is about 250 KHz and the frequency response curve is shown in Figure 3.5.

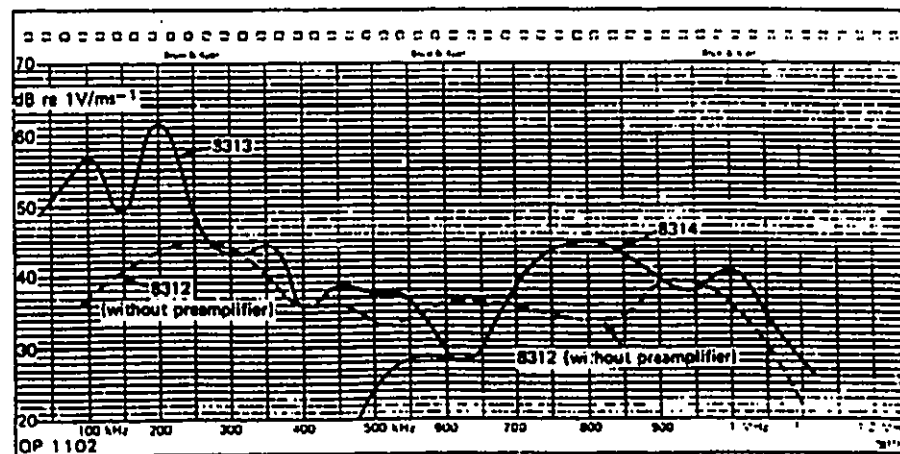


Figure 3.5. Frequency response curves for AE transducer.

A B&K model 2638 wideband conditioning amplifier was employed to filter the acquired AE signal to the frequency range from 100 kHz to 1 MHz. It also provided amplification of the typically very low signal.

3.5. Digital Oscilloscope

A programmable digital oscilloscope, Norland Prowler digital oscilloscope, was employed to acquire and process the AE signal. It is an oscilloscope which is capable of acquiring signals from DC up to 20 MHz and is equipped with preprogrammed math functions, auto programmable functions, and can be controlled by a computer. The free run or trigger mode was used to hold the data on the screen. The captured data was first processed with the built-in math processor, and was then transferred to the IBM personal computer to be saved in storage. The IEEE 488 interface card was used to save fast binary data and the RS232 card for fast decimal data.

3.6. True RMS Voltmeter

Figure 3.6 shows the overall block diagram of the RMS volt meter. To obtain the overall RMS voltage change during the drilling operation, the Fluke True RMS voltmeter was employed. The instrument consists of a signal conditioner, RMS converter, A/D converter, controller and display. The drilling signals which

are transmitted through the B&K 8312 transducer are filtered to the frequency range of 100 kHz to 1 MHz. The signal conditioner insures that the varying levels of instrument input voltages are properly scaled before being applied to the RMS converter. This signal is converted to RMS voltage and saved to the IBM-PC through the A/D converter, controller and IEEE card.

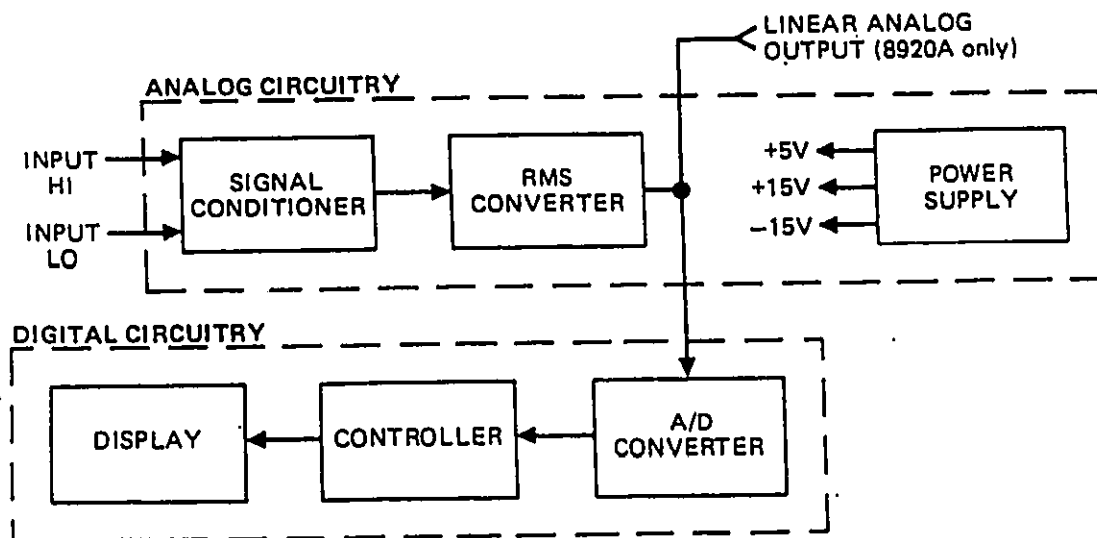


Figure 3.6. Overall Block Diagram of True RMS Meter.

3.7. Pulse Counter

The count and count rate method is one of the most popular methods of monitoring acoustic emission signal even though it is very sensitive to the threshold value which must be appropriately selected. A 24-bit pulse counter was employed and the operation is illustrated in Figure 3.7.

The drilling signal which is transmitted through the B&K 8312 transducer, is filtered to the frequency range of 100 kHz to 1 MHz. The reference voltage (threshold voltage) is determined by trial and error after several drilling operations and is set on the calibration voltage indicator(6) in Figure 3.7. Two control switches, one for rough control and the other one fine control, are provided to adjust the reference voltage(1) to the calibration voltage which is indicated by the voltmeter. The voltage level comparator(2) compares the amplitude of the drilled signal with the reference voltage(1) and generates a pulse every time the amplitude of the drilling signal equals or exceeds the reference voltage level. Three 8-bit counters(3) count the number of such pulses and the values are placed into the temporary storage registers(4) with the computer command. The CPU then sends commands to read the MSB (most significant byte) and LSB (least significant byte) and then the values are converted into a count value. The temporary storage is used to prevent the error of counts due to the time delay between the reading of the MSB and LSB. The performance of the counter was tested at different input

frequencies. Sine waves with the frequency of 1 MHz were generated with the use of WAVETEK Model182 Function Generator and threshold voltage was set up with the reference voltage indicator. The reference voltages were monitored by means of the Philip PM2423 Multimeter to avoid unexpected changes of the reference voltage level.

The counts per second, as measured by the counter, were expected to equal the input signal frequency. However the results of the test show some degree of error between the input frequency and the count rate, as shown in Table 3.3. The average percentage error of the pulse counter is 3%. Appropriate corrections were made to the data collected during actual experiments conducted with the system. Since the actual frequency of AE detected is not known, the average error correction is made on all the data collected.

Time hr:min:sec	Number of measurement of 1 MHz signal				
	#1	#2	#3	#4	#5
00:00:01	972961	974931	973746	974920	973739
00:00:02	973826	974938	973757	974917	974828
00:00:03	974955	974961	973762	974925	974824
00:00:04	974982	974965	973787	974913	974806
00:00:05	974914	974955	973828	974907	974821
00:00:06	974898	974941	974915	974875	974850
00:00:07	974941	974938	974925	974935	974843
00:00:08	974999	974952	974901	974905	974878

Table 3.3. Performance test of the counter.

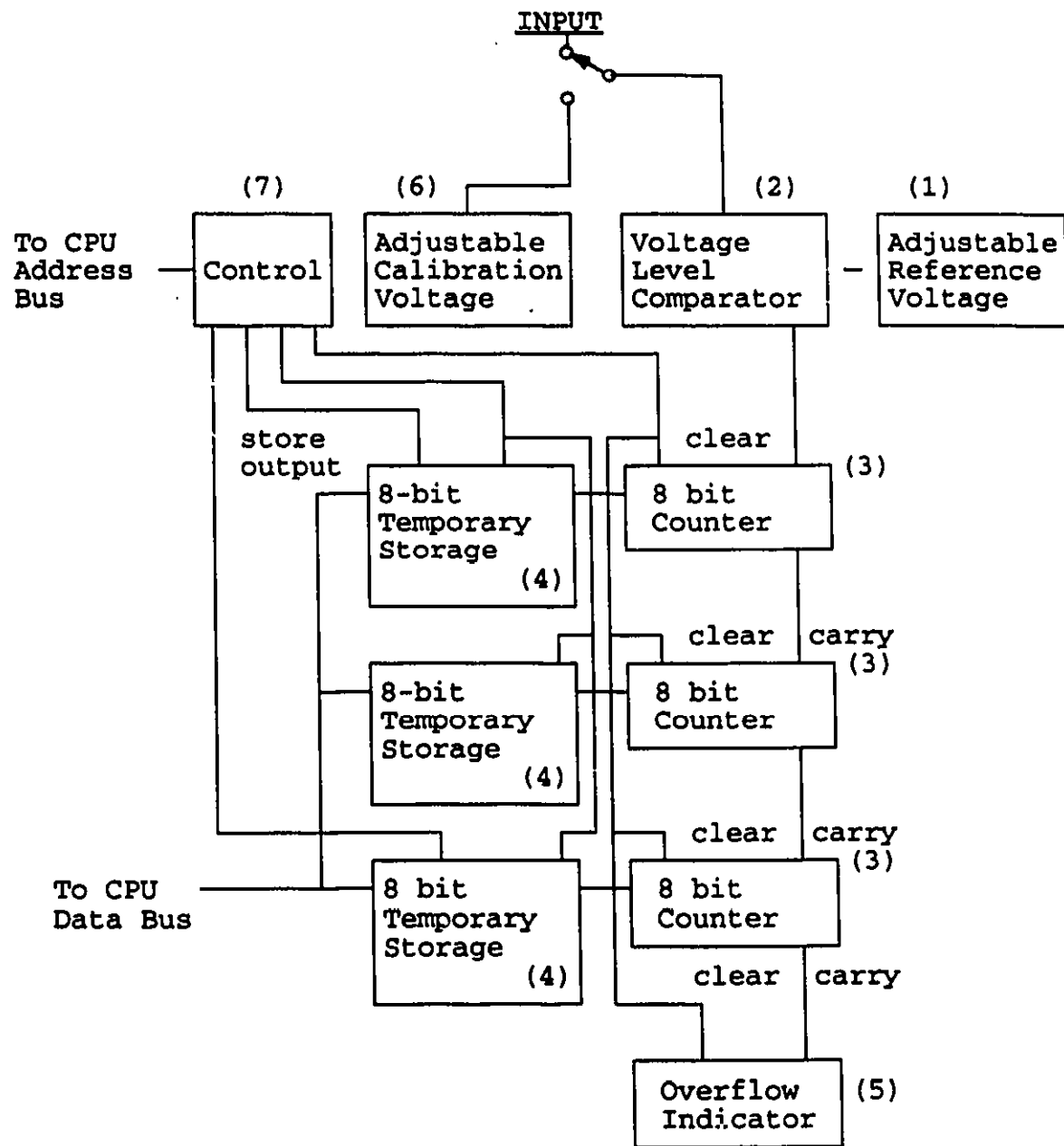


Figure 3.7. Block diagram of the counter.

3.8. Oscilloscope

Hewlett-Packard 1201A, 10 MHz dualbeam oscilloscope was used for viewing the real time signals.

3.9. Drill Wear Measurements

Measurement of drill wear was performed with a travelling microscope which is equipped with a dial gage, as shown in Figure 3.9. The microscope has a magnification of 20X and the resolution of dial gage is 0.001". The drill wear in this study is represented by the corner wear of the cutting edge, as shown in Figure 3.8, which is recommended by Amini [1] and Kanai [37]. Amini measured the wear of the high speed steel twist drills with the use of radioactivity method and confirmed these results by optical measurements. He measured two types of drill wear, flank wear and corner wear and the results show very close trends. Kanai[82] measured the drill wear with the optical method and he recommended the outer corner measurements for drill wear since it is easier and provides more consistent results.

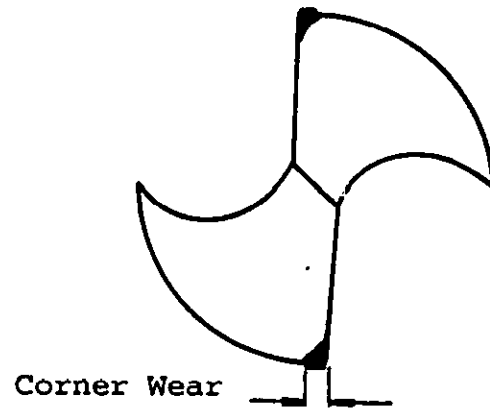


Figure 3.8. Definition of drill wear in this study.

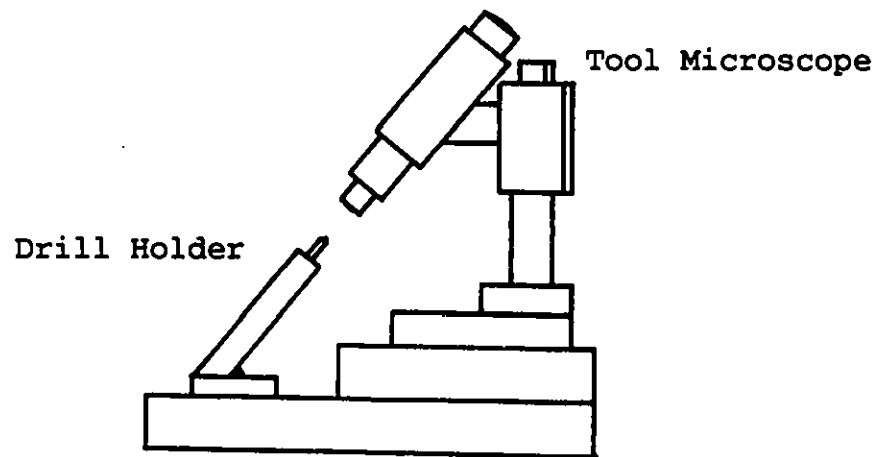


Figure 3.9. Schematics of drill wear measurements.

3.10. Measurement of chisel edge to drill outer diameter run-out tolerance

Braun and et al[31] explained the behavior of the drill during cutting as follows: due to the production tolerances, a drill is slightly asymmetric; therefore, it only wears at one lip until the heights of both lips are equal. The second lip, now sharper, starts cutting. This alternating process continues until both lips have no more clearance at the margin. At this time, the drill sticks into the workpiece and breaks if the drilling process is not stopped in time.

To observe the nonsymmetry of the drill lips, run-out tolerances from the chisel edge to the drill outer diameter were measured. As shown in Figure 3.10, the drill was located in the v-block. The drill chisel edge was placed in the stopper and then the drill was rotated. The dial gage, which had a travelling guide, measured the run-out tolerances. Total indicator reading from the edge to the outer diameter was recorded.

Dial Gage

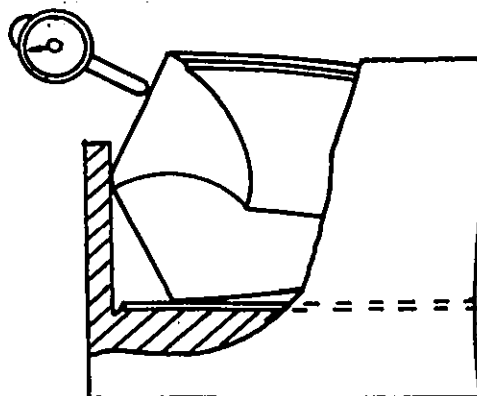


Figure 3.10. Diagram of run-cut tolerance measurements.

CHAPTER 4

DATA PROCESSING

Typical AE signals, which are emitted during the drilling process, contain continuous and burst type emissions with distinctly different characteristics. These signals are nondeterministic and random in nature, as it will be shown later in Figures 5.6, 5.7 and 5.8. To analyze those signals, a special processing scheme was developed and will be presented in this chapter. It consists of the following major components: data acquisition, data analysis, and computer program.

4.1. Data Acquisition

The AE signal picked up by an accelerometer, is sent to a signal conditioning unit, B&K 2638 Wideband Amplifier, to amplify the weak AE signal and to filter it to the desired frequency range. Since AE has very high frequency in the range from 100 kHz to as high as 2 MHz, the filter bandwidth is selected to that range. The filtered signals are then sent to three devices, each performing a different aspect of signal processing scheme. These devices are all remotely controlled by an IBM PC XT computer and the commands to control these devices will be discussed later in the computer implementation section. The three devices are: pulse counter, Fluke TRMS voltmeter, and Prowler digital oscilloscope.

The schematic diagram of the data acquisition process can be seen in Figure 3.2.

4.1.1. Pulse Counter

This card resided in one of the expansion slots in the computer. The filtered AE signals are continuously sent to the card and their amplitudes are compared with some threshold level. A pulse is generated if the amplitude is greater than the threshold level and the pulse count is cumulatively stored in three consecutive bytes in the computer memory.

In order to use the card, the user has to decide on how often to extract the pulse count from the three bytes. In the present case, the pulse count is extracted as often as the computer is capable. The total pulse count is calculated using equation (33).

$$\text{COUNT} = \text{Byte\#1} * 2^{16} + \text{Byte\#2} * 2^8 + \text{Byte\#3} \quad (33)$$

The procedure used to extract the pulse count in a drilling sequence is summarized by a flow chart as shown in Figure 3.7. It consists of firstly clearing the three bytes in the memory, then start and stop the extraction process for the instances when the drilling sequence begins and when it is completed. Since the number of AE pulse counts is dependent on the threshold amplitude and the time involved in a drilling sequence, the count values obtained are normalized in order to eliminate some of those

variabilities. These pulse counts are stored on a floppy disk for further analysis.

4.1.2. Fluke TRMS Voltmeter

The Fluke TRMS voltmeter is a device used to convert the AE signal in the time domain to its RMS equivalence. These RMS values are known as the true RMS because there is no time period involved. The output from the Fluke TRMS voltmeter is sent to the computer via the IEEE-488 interface card. The procedure used to capture the RMS values from the Fluke TRMS voltmeter is the same as that used to capture pulse counts as demonstrated by the flow chart shown in Figure 3.6. These TRMS values are also stored on a floppy disk for further processing.

4.1.3. Prowler Digital Oscilloscope

The Prowler digital oscilloscope, as discussed in chapter 3, is powerful, programmable, and has two types of communication capability with a computer, namely, RS232 and IEEE-488. Data obtained from the Prowler can either be in decimal or in binary format. As speed is a very essential element in this scheme of things, most of the data transferred from the Prowler used the binary format via the IEEE-488 interface bus, and was stored directly onto the floppy disk. Data transferred in binary format not only is fast but also consumes less space in storage. Two

different sampling rates were used in this research namely, 1 MHz and 2 MHz.

4.2. Data analysis

In general, the signal can be processed in two different domains, which are the time and frequency domain. For this research, the data or sources for the data analysis consist of the following:

1. Pulse counts from the counter.
2. RMS values obtained from the Fluke RMS voltmeter.
3. Raw data from the Prowler digital oscilloscope.

In the frequency domain analysis, as the available frequency analyzers are not capable of handling signals of such high frequencies, a Sande-Tukey Fast Fourier algorithm was implemented on the computer. Although there are other, more sophisticated and powerful Fast Fourier algorithms available, this routine provides just as good results in this application.

4.2.1. Frequency Domain

The two most important potential problems in frequency domain analysis are aliasing and leakage. Aliasing, in general, can be eliminated if the sampling rate is greater than twice the highest frequency of the input. It is also known as fold-over or mixing. In this research, the highest frequency of interest is at least

500 kHz, therefore, the sampling rates used were at least 1 MHz. Leakage is defined as the smearing of energy throughout the frequency ranges. Generally, it can be minimized by a proper selection of windowing in the input data. There are many windowing functions that can be used to window the data, such as Hanning, Uniform, Flat-top window and others. Selection of the windowing function is very much dependent on the of nature of the signal encountered. In this research, Hanning window was used because of the random nature of the AE signal and it is incorporated in the Fast Fourier routine. The data captured from the Prowler are first converted to decimal form, if necessary, and are then sent to the Fast Fourier routine to obtain the frequency spectrum. Three descriptors are extracted from the frequency spectrum, which are peak amplitude, the total spectrum RMS, and bandwidth RMS. Bandwidth RMS is defined as the RMS value within some frequency band. The frequencies, which were bands selected, correspond to the regions where more AE activities occurs. Equation (34) is used to calculate the RMS value.

$$RMS = \sqrt{\frac{(\sum_{i=1}^n X_i^2)}{N}} \quad (34)$$

where X_i = amplitude

N = Total number of values.

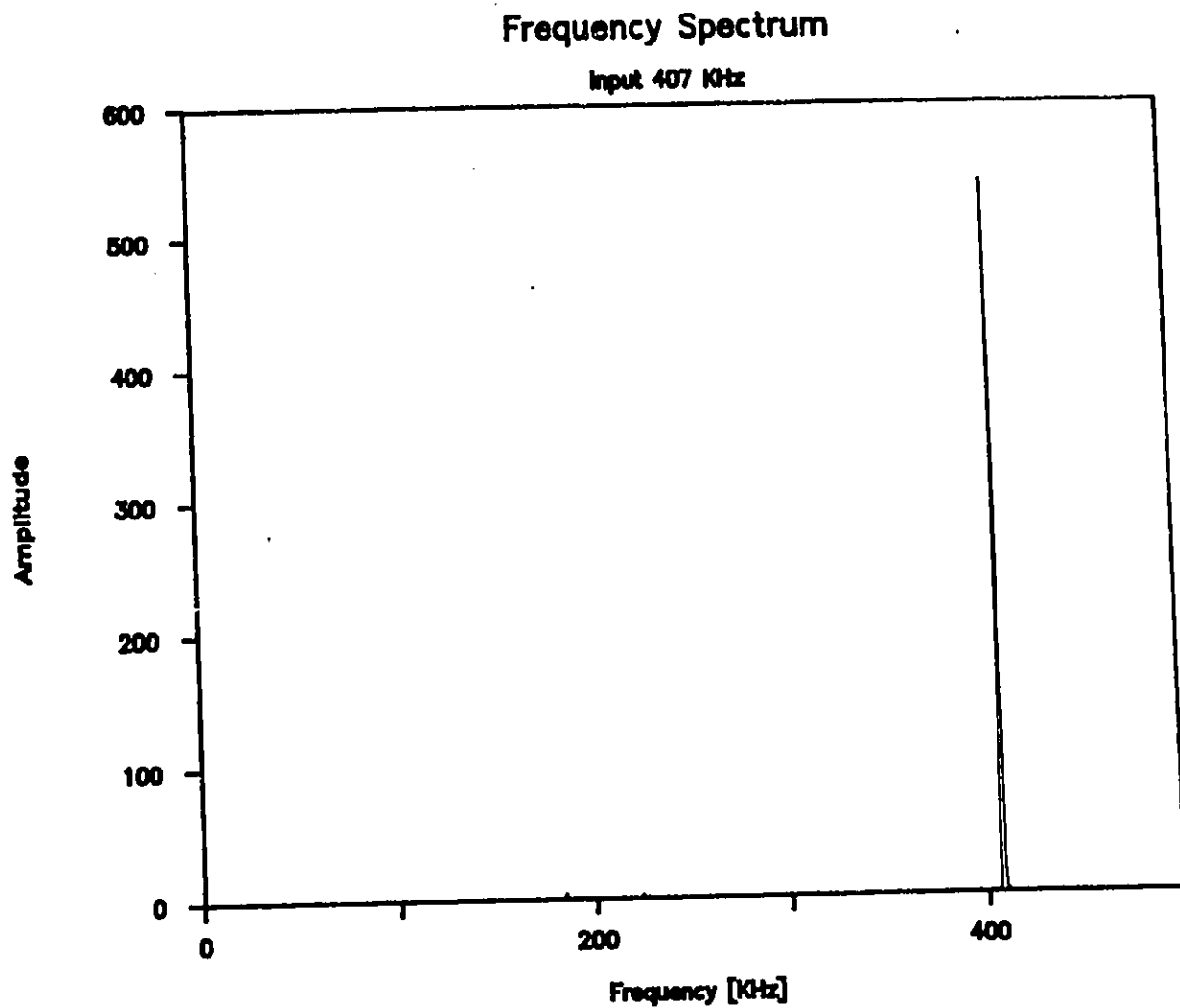


Figure 4.1. Validation of FFT program with a known input frequency at 407 KHz.

4.2.2. Time domain

Time domain analysis can be briefly stated as a study of how the signal behaves with respect to time. Therefore, pulse counts, TRMS values, and data obtained from the Prowler, can all be considered as time domain data.

No additional data analysis is necessary for both Pulse counts and TRMS values, except doing the time plot, to extract features such as trend, outliers, etc.

Due to the random nature of the signal, statistical descriptors, such as mean, standard deviation, skew, kurtosis, and RMS were also calculated. The skewness is a measure of the asymmetry of the data distribution, as shown in Figure 4.3, and the kurtosis is a measure of the peakedness of the data distribution, as shown in Figure 4.4. Before performing any statistical calculation, the data are grouped to a certain number (i.e., 100 groups) of same interval amplitudes to obtain the frequency distribution of the signal, as shown in Figure 5.31.

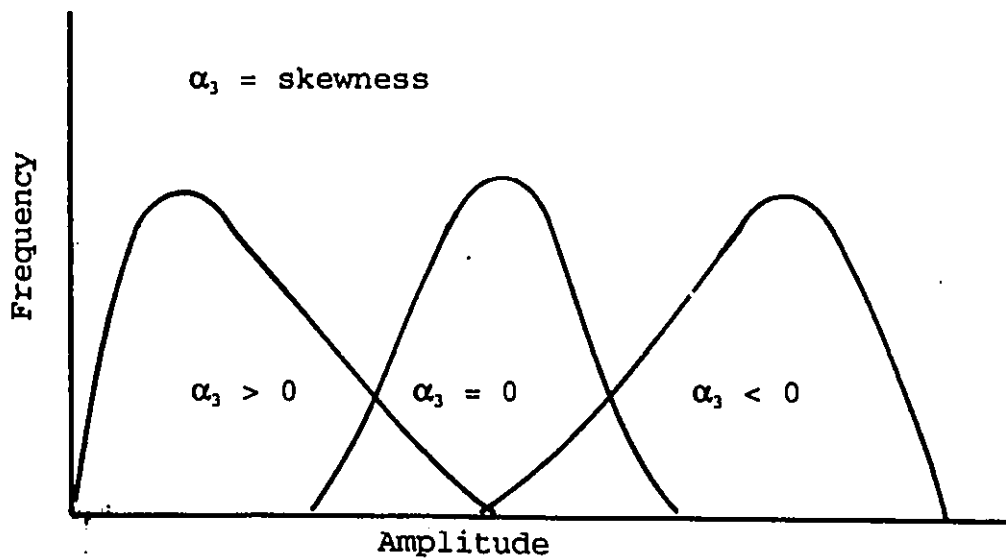


Figure 4.3. Illustration of the relationship between skewness and data distribution.

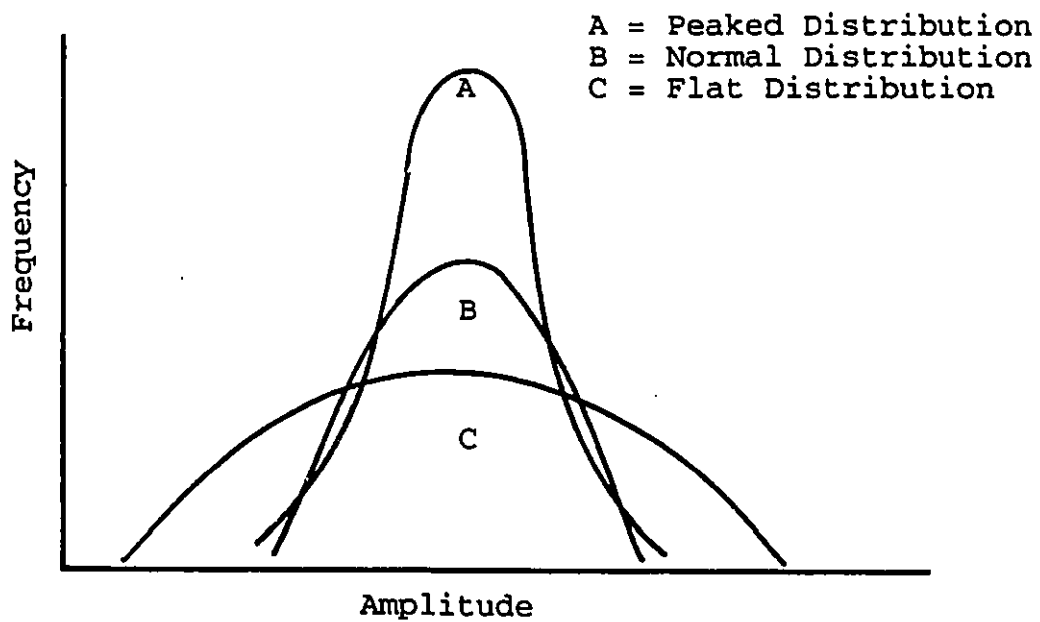


Figure 4.4. Illustration of the relationship between kurtosis and data distribution.

A significant advantage of performing statistical calculations on the grouped data over the use of ungrouped data, is the noticeable reduction in the computation time. The formulae used to calculate the statistical descriptors are;

$$m_1 = \text{mean} = \frac{\sum_{i=1}^n y_i}{n} = \bar{y}$$

$$s = \text{standard deviation} = \sqrt{\frac{\sum_{i=1}^n (y_i - \bar{y})^2}{n}} \quad (35)$$

$$\alpha_3 = \text{skewness} = \frac{\sum_{i=1}^n \left[\frac{(y_i - \bar{y})}{s} \right]^3}{n} \quad (36)$$

$$\alpha_4 = \text{kurtosis} = \frac{\sum_{i=1}^n \left[\frac{(y_i - \bar{y})}{s} \right]^4}{n} \quad (37)$$

4.3. Computer Programming

The computer was the most essential device in this AE signal processing scheme. It sends commands to control the activities of the peripheral devices, performs data analysis, instructs storage of data onto the floppy disk, and enables the data presentation on its monitor. All the devices connected to the computer are shown in Figure 3.2. In this research, two computer languages were used to write programs, namely Basic and C. To be more specific, they are Quickbasic version 4.5 and Turbo C version 2. Basic programs are written mainly for establishing communication between devices, i.e., send commands to and receive data from the device. Tasks that require extensive number crunching are handled by programs written in C (Turbo C), such as the Fourier Transforms. In general, if successful communication is required between computer and its peripheral devices, the computer has to know: the type of interface available on the device, the device's unique primary and secondary address if the interface is IEEE-488, the format of the data sent out, such as binary, decimal, etc, and also the data transfer rate. Even though the data transferred can be in binary or decimal notation, they are always send and received as character strings, hence it is the user responsibility to break down and extract their binary or decimal equivalence. Tables 4.1 shows those interface information between the computer and its peripheral devices.

Device	Interface Type	Data Format	Primary Address	Secondary Address
Fluke RMS Voltmeter	IEEE-488	Decimal	6	1
Prowler Digital Oscilloscope	IEEE-488	Decimal or Binary	3	*
	RS232	Decimal or Binary	*	*
Plotter (HP7475A)	IEEE-488	String	4	*
* denotes not applicable/available.				

Table 4.1. Interfacing information of the devices.

4.3.1. Communication Between the Fluke RMS Voltmeter and the Computer

As mentioned before, the communication between the Fluke TRMS voltmeter and computer is through the IEEE-488 interface, also known as GPIB or HP-IB interface. Like any other device with an IEEE-488 interface, it has its own unique device address. In this case, it was set to 6 and the RMS value is stored at the secondary address of 1, as described in Table 4.1. The set of commands, written in Basic and used to extract readings from the TRMS voltmeter is given below and the data are transferred out as fast as the computer can handle.

```
PARAM$="INIT/1/&H330/P/":GOSUB 10000 'INITIALIZE THE CARD
PARAM$="RD.STR/6/1//EOI/":GOSUB 10000 'READ RMS VALUE
```

```
RMS(I)=VAL(MID$(DATA.STRING$,1,8))
```

```
'STORE RMS VALUE
```

As can be seen, the communication is established by first having a desired command character string assigned to "PARAM\$", it is then sent to a subroutine that contains all the IEEE-488 interface routines for interpretation by the statement "GOSUB 10000", and finally the appropriate action is taken between the two devices. Those IEEE-488 interface routines used, are supplied by the manufacturer when the interface card was purchased and they are written in Basic. The data received is stored as a string character assigned to "DATA.STRING\$" which can hold a maximum of 255 characters at one time. More detail explanation of those commands can be found in IEEE-488 interface card manual.

4.3.2. Communication Between Prowler and the Computer

Prowler is capable of two types of communication, namely, using RS232 or IEEE-488 and it can transfer the data out either in decimal or binary format. In this research, most of the data received from Prowler are in binary format due to its high transfer rate and compactness, which is, binary format uses only two bytes whereas decimal format requires 13 bytes to store. Since Prowler is programmable, a simple program was written and stored in its volatile memory, with the sole purpose of sending the desired data out to the computer upon request. Therefore, the set of commands used for the communication is given as follow;

```
PARAM$="INIT/1/&H330/P/":GOSUB 10000 'INITIALIZE THE CARD  
DATA.STRING$="T"+CHR$(255) 'COMMAND TO RUN THE
```

```
PARAM$="WR.STR/3//EOS/":GOSUB 10000 'PROGRAM IN PROWLER  
PARAM$="RD.TO.FILE/3//EOS/"+ "A:TEMP.DAT"+"/"  
GOSUB 10000 'READ & STORE DATA ON FILE
```

As can be seen from the command set, the data are temporarily stored in a file called "TEMP.DAT" and are read back for extraction, once the transfer process is terminated between the computer and Prowler.

4.3.3. Computer Program

Several task-oriented programs were developed in the course of this research to do specific tasks, such as, performing statistical analysis, acquiring data from Prowler, etc. However, only two programs are included in the discussion:

1. tool condition monitoring,
2. curve-fit and plotting.

4.3.3.1. Tool Condition Monitoring

This is a menu-driven, user friendly program which incorporates all the task-oriented programs used in this research. The program is implemented using QuickBasic and supports three

different graphic drivers, namely, Hercules, CGA, and EGA. Due to the complexity of the program, a set of error codes and handling routines was also included. Basically, it addresses the following five tasks:

1. data acquisition,
2. data analysis,
3. data presentation,
4. data storage, and
5. data reduction or diagnostics.

Data acquisition involves the process of acquiring data from the Pulse counter, TRMS voltmeter, Prowler digital oscilloscope, and it also retrieves data previously stored on the diskette.

Data analysis involves performing statistical analysis in the time domain, and obtaining the frequency spectrum in the frequency domain.

Data presentation allows plotting of the pulse counts, TRMS values, raw data, frequency spectrum, and frequency distribution with statistical results on the computer monitor.

Data storage enables pulse counts, TRMS values, raw data, frequency spectrum, and statistical results to be stored on the diskette.

Data reduction or diagnostics involve some prior knowledge of the response of some descriptors with the condition of the drill at any stage. The newly calculated descriptor's value is compared with that knowledge to determine the condition of the drill.

Figure 4.4, shows the different menus which correspond to the

different tasks that the program is capable of performing. The program listing is also included in Appendix II.

4.3.3.2. Curve-fit and Plotting

This is an utility program used to do data editing and manipulation, plotting, and also curve fitting. Data can be either input from keyboard or retrieved from the diskette. In this program, data manipulation involves tasks like: adding data, changing data, deleting data, and viewing data in the data set and can also save data to diskette. Again, this program is implemented using Quickbasic and supports three graphic drivers. The curve fitting procedure used is the least square fit and supports five different families of curves, namely: linear, log, exponential, power, and polynomial. In addition to having a capability of overlay plots, curve fit the data, and display on screen, it can also direct the output to the HP 7475A plotter and printer, if desired.

It is also a menu driven user friendly program with the menus available as shown in Figure 4.5. The program listing is included in Appendix II.

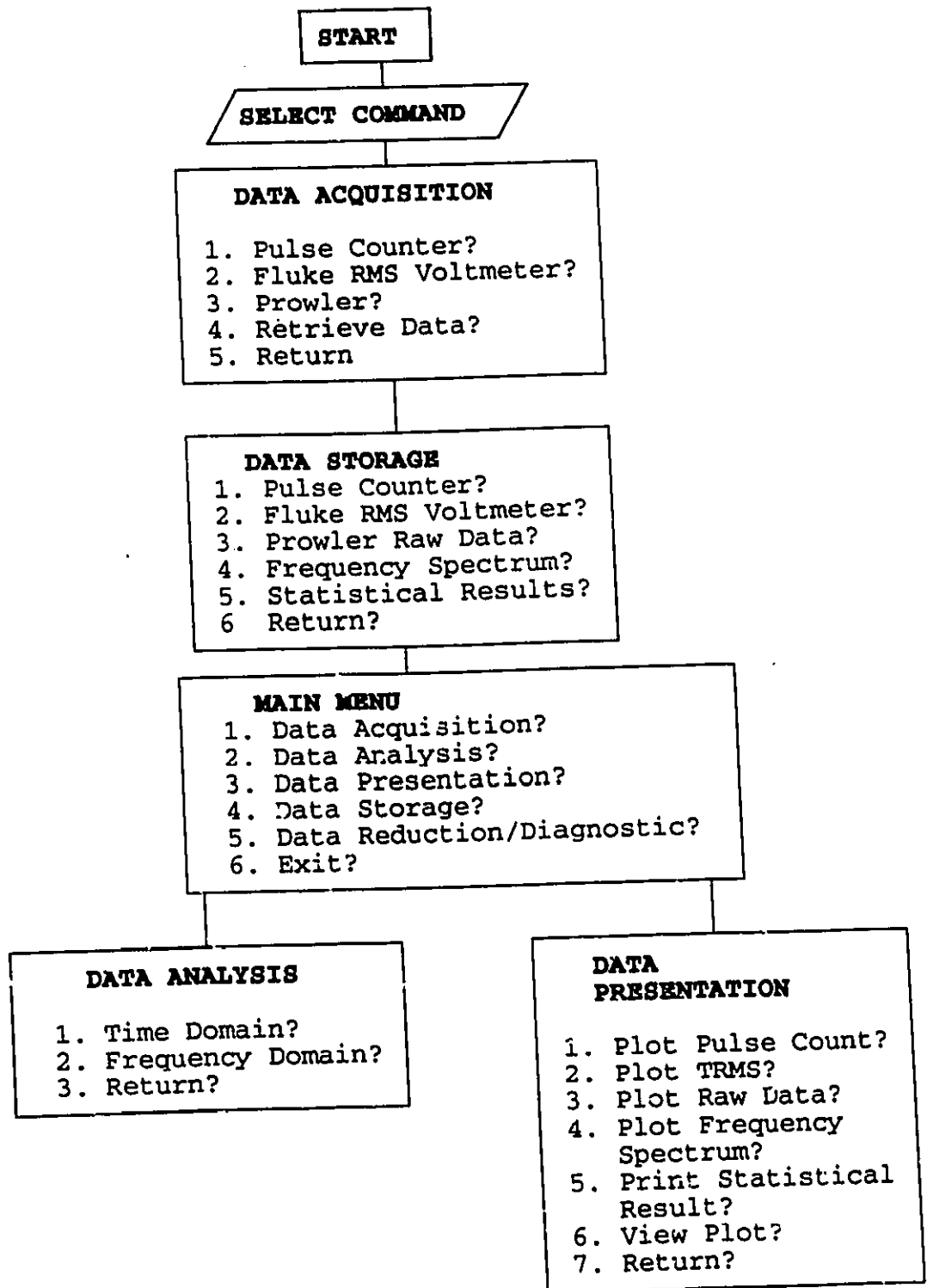


Figure 4.5. Menus available in the tool condition monitoring program.

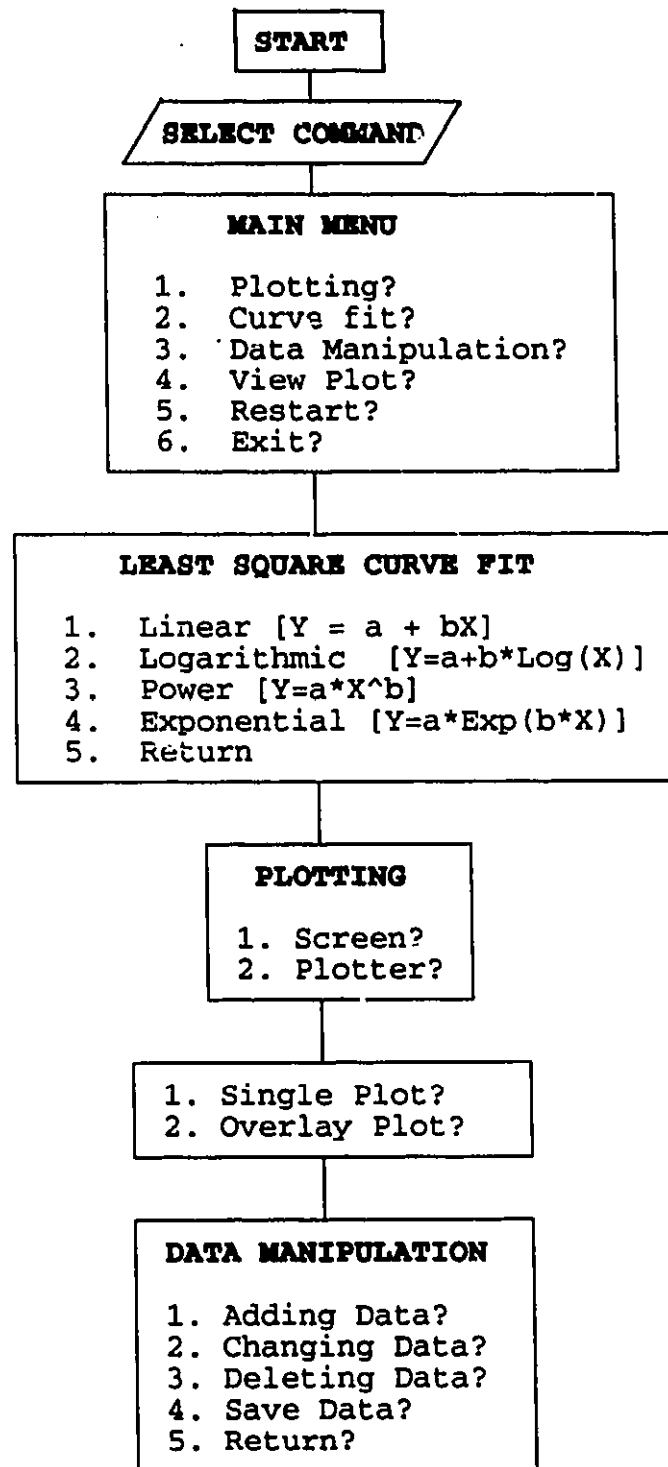


Figure 4.6. Menus available in curve fit and plotting program.

CHAPTER 5.

RESULTS

The experimental results of drill condition monitoring with the use of acoustic emission signal are presented in this chapter. The parameters which are measured by a direct method, e.g., drill wear and symmetry of chisel edge, are dealt with at the beginning of the chapter. This is followed by the discussion of the results of AE signal analyses which were obtained from 78 drills. The results, obtained by direct measurements of the drill wear and by indirect measurements with AE signals are also compared and discussed.

In this study, one set of data represents the results obtained from initial drilling with a new drill to the point where imminent or complete failure of the drill occurs. The normalized drill life is defined as the number of actual drilled holes divided by the total number of drilled holes at failure, which is used as one of the variables. The quantitative relationships between pertinent descriptors, which are determined by means of the polynomial or exponential regression analysis with the method of least squares, against normalized drill life, are also plotted and discussed in this chapter.

5.1. Mean Life of Drills

In this study, drilling was terminated when the condition was reached at one of the three criteria of drill failure. The total drilling time from new drilling to failure was then calculated. The drill failure was defined in this study either by the onset of a scream, drilling operation with radial chatter marks at the bottom of the hole, by chipping out of the corners of the drill, or rotation of the drill in the chuck. The observed drill life is plotted against V^2F , where the V is the speed and F is the feed of drilling. The mean life of the drill at different V^2F was calculated with the method of a logarithmic transformation of the random variables[78] since in this experiment the ratio of the standard deviation of the drill life to the arithmetic mean of the drill life is greater than $1/3$. The mean life of the drill decreased with a logarithmic relationship against the increase of V^2F , as shown in Figures 5.1 and 5.2, and the trend was similar to that observed by Singpurwalla[78]. The procedure to obtain the mean life equation will be discussed in chapter 6.

5.2. Pattern of Drill Wear

The drill wear in this study was defined as the corner wear of the drill edge, as shown in Figure 3.8. This wear was measured after every hole was drilled. The measurement sequences were

Drill Life vs. $V^2 \cdot F$

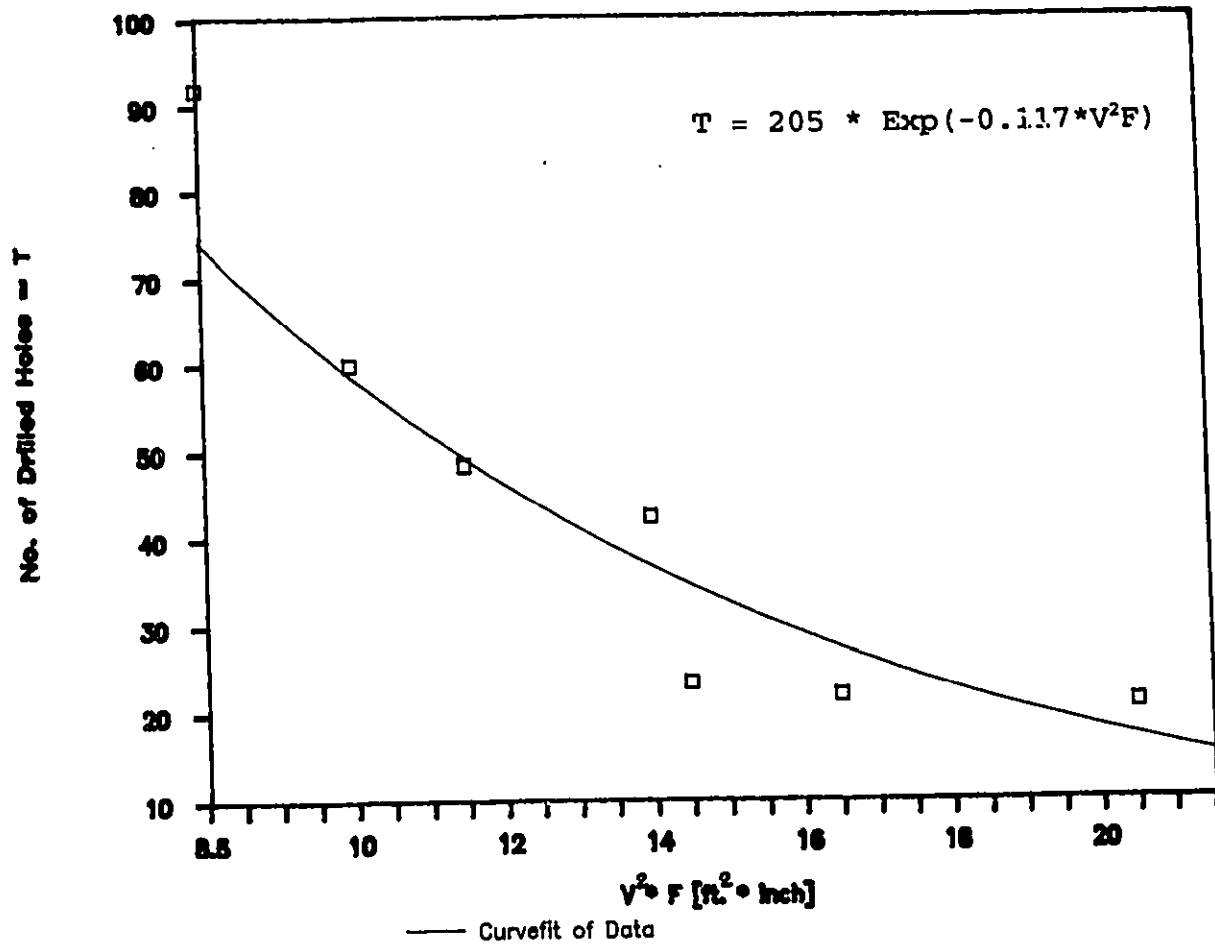


Figure 5.1. Mean life of drill vs. $V^2 \cdot F$.

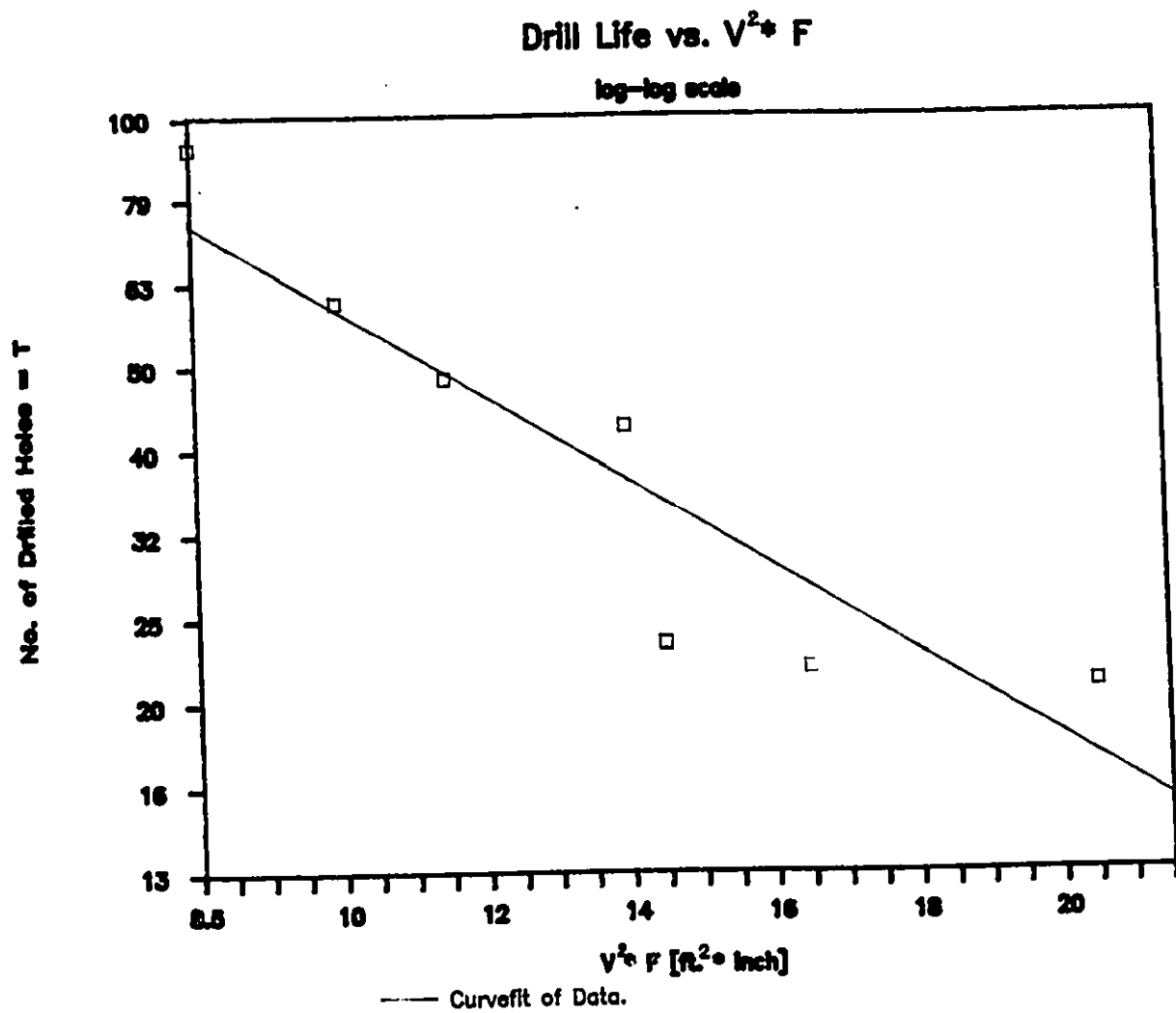


Figure 5.2. Mean life of drill vs. $V^2 \cdot F$ (log-log scale).

repeated for seventy eight sets of drills. Two different patterns of wear curves were observed. In the first type, as shown in Figure 5.3, initially the wear was very rapid and relatively random, this was followed by a phase of gradual wear increase until about 60 percent of drill life, and finally a very rapid rate of wear until failure. In the second type, a rapid initial increase of wear is followed by a gradual increase until failure, as shown in Figure 5.4.

5.3. The Run-Out of the Drill Chisel-edge to O.D.

As previously discussed, the patterns of drill wear consisted of at least two different stages, not like the wear patterns of single edge cutting tools which behave almost linearly with the increase of cutting time. Braun [6] observed that the unsymmetry of the chisel edge of new drills is the main reason for the uneven wear at both sides of the chisel edges, and that three stages of drill wear were observed by Braun. The average of the chisel edge to drill diameter run-out, which is defined as total indicator reading from chisel edge to drill diameter with rotating the drill, for twelve of 1/8" diameter drills used in this study, was measured and determined to vary from 0.6 to 1.3 thousandth of an inch. To check the confidence of these measurements, they were compared with the run-out measurements, from chisel edge of the drill to the outside diameter of the drill, which were obtained in one of the largest North American auto

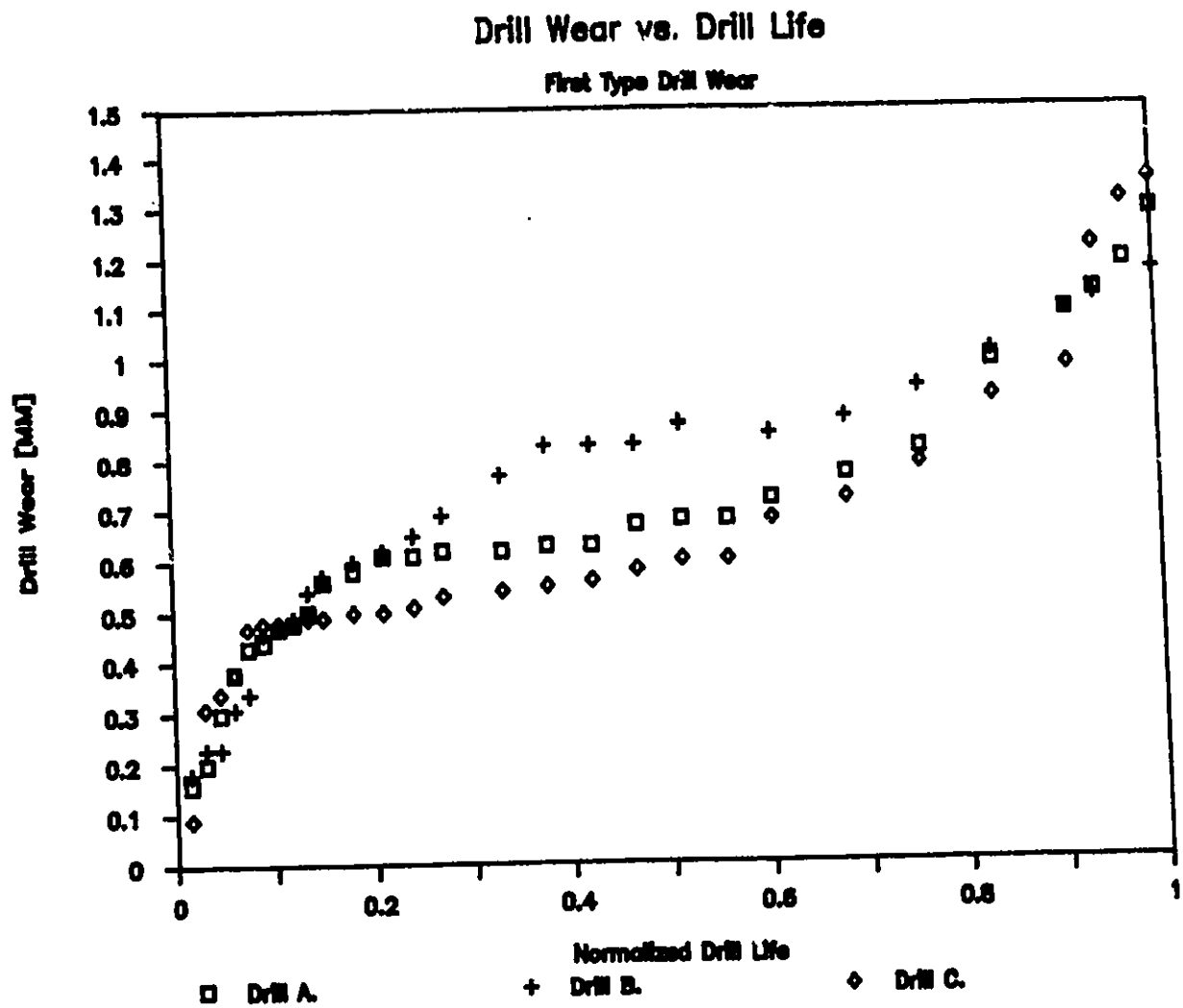


Figure 5.3. First type drill wear vs. normalized drill life.

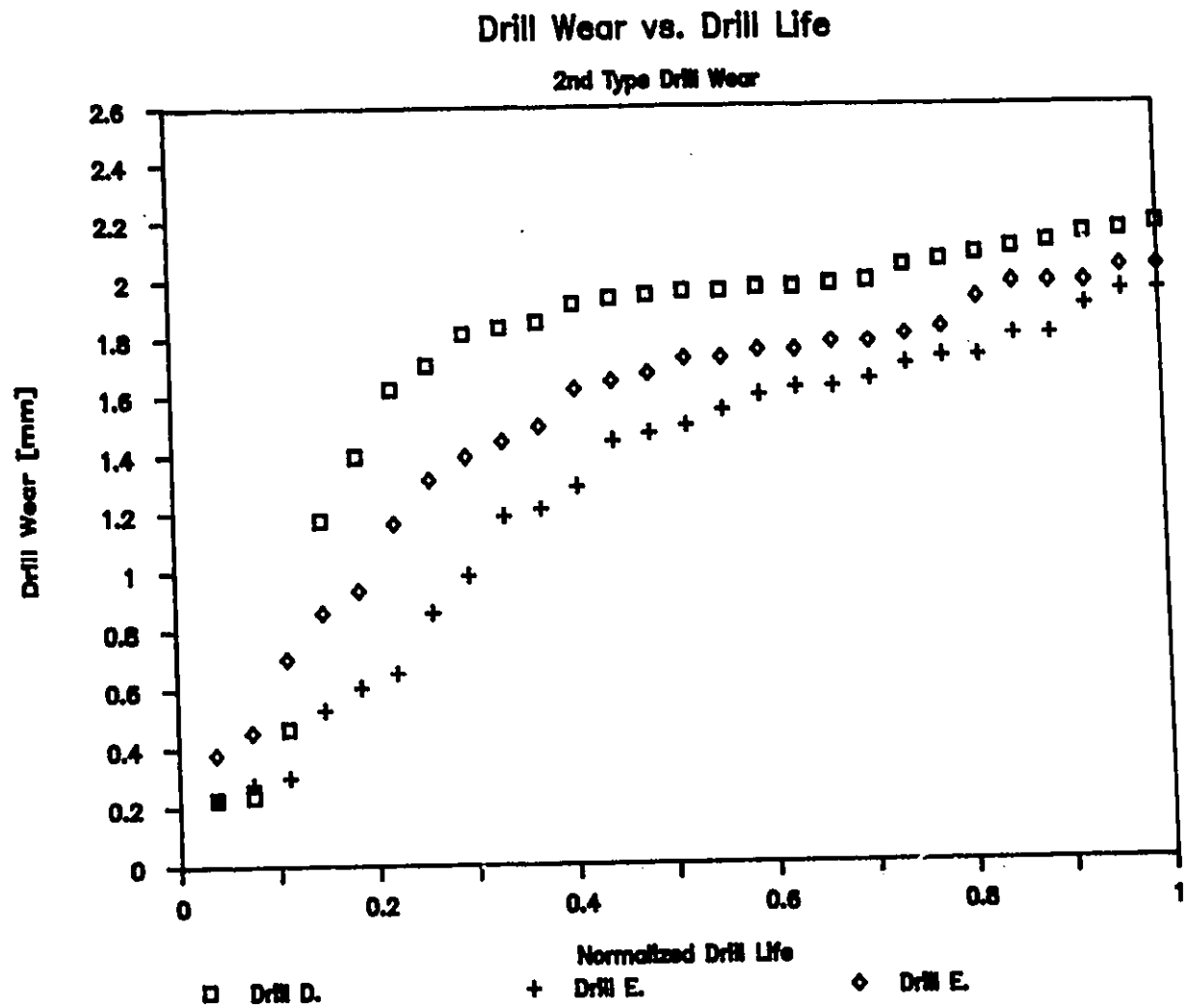


Figure 5.4. Second type drill wear vs. normalized drill life.

Part Name DRILL Part No. _____
 Operation No. CHISEL EDGE TO DRILL Machine _____
 UCL = _____ LCL = _____ Inspects _____

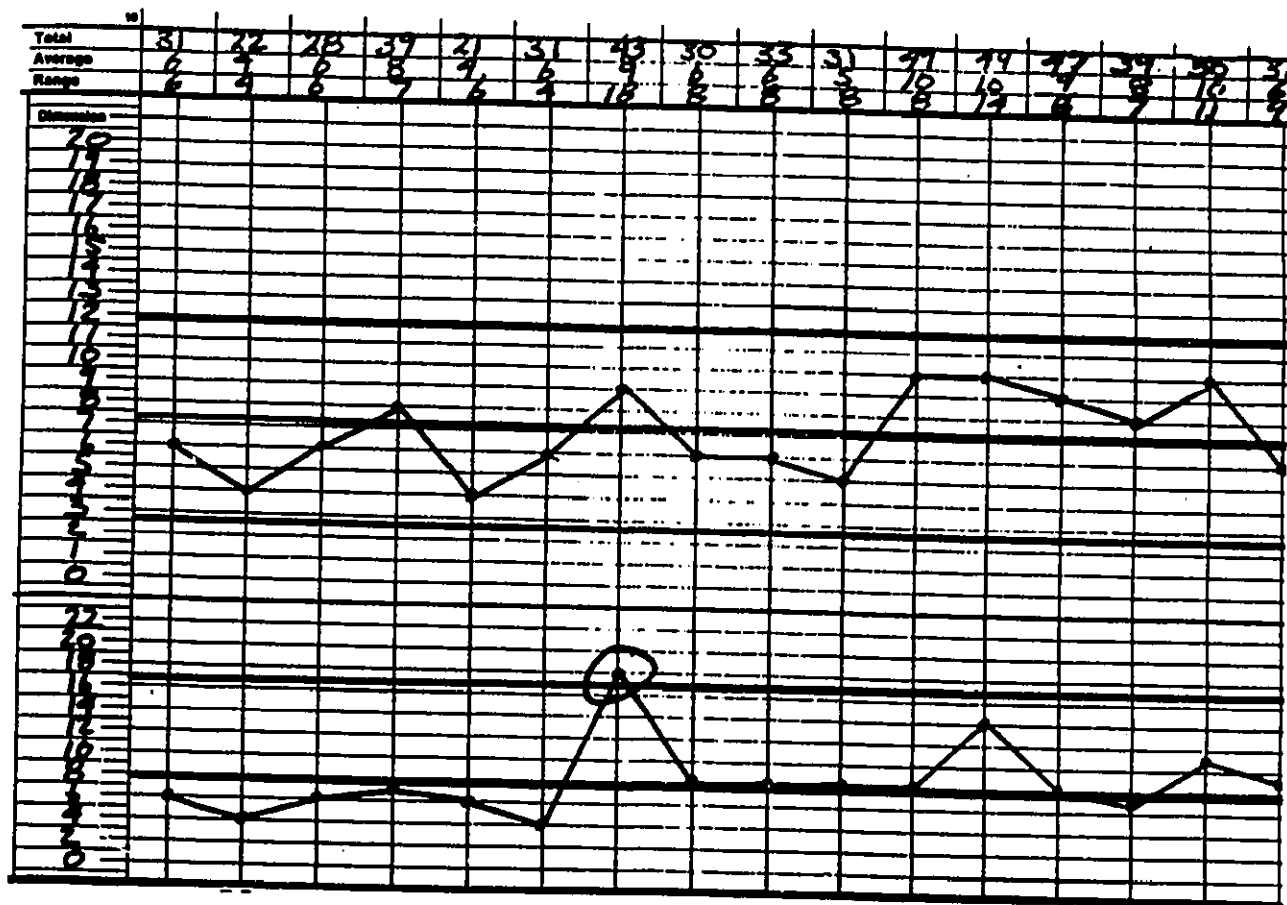


Figure 5.5. Measurement chart of run-out tolerance.

company's engine plant tool room. Out of two hundred sixty measurements of the 0.296 inch drills, none has zero run-out tolerance and the average of the measurements was determined as 0.7 thousandth of an inch, as shown in Figure 5.5.

5.4. Acoustic Emission Signal Analysis

Acoustic emission signals, which were picked up by a transducer and sent to B&K 2638 wideband amplifier to amplify the weak AE signals and filter from 100 kHz to 1 MHz, were analyzed by means of time domain and frequency domain analysis.

AE count and TRMS(true root mean square) measurements were employed for the continuous time signal analysis. Both methods are very attractive because of the low cost of implementation, less data processing time compared with other methods and their capability to analyze the entire period of drilling. However, the output data from the AE counter and TRMS meter were already processed, hence recalling the original raw data for further analysis was not possible.

The nature of the AE signal from drilling was observed by recalling the digitized raw data which was stored on the diskettes using the digital oscilloscope and personal computer. The AE signals, in terms of time-amplitude signal, from a new drill and worn drills were plotted and observed. Statistical parameters, i.e., amplitude distribution, RMS, standard deviation, mean, kurtosis, and skew, were determined. However, the limited data

storage capacity of the oscilloscope and computer, and longer data processing time, compared to the AE counter and TRMS meter, are a definite disadvantage.

Frequency analysis of the AE signal from drilling was also carried out in an attempt to characterize the drilling events in more detail.

The obtained results and the time series and frequency analyses of AE data are compared and discussed in the following sections.

5.4.1. Time Domain Signal Analysis

During drilling, the AE signal from the transducers was amplified, highpass filtered and digitized by the Prowler oscilloscope at a 1 MHz sampling rate and stored on diskettes. A set of 16K(16384) points of the AE signal was recalled to the computer, analyzed and plotted. The general trend of the signal amplitude change from initial drilling to the drill failure was observed. As can be seen from Figures 5.6 and 5.7, the amplitudes initially were very low and reasonably constant. Near drill failure, the amplitudes were very high and inconsistent, as shown in Figures 5.8 and 5.9. The comparison of amplitudes was very time consuming, and a clear trend in their changes with the drilling time was not evident.

The significant fluctuations in the amplitudes of the signal occurred consistently when drill failure was imminent,

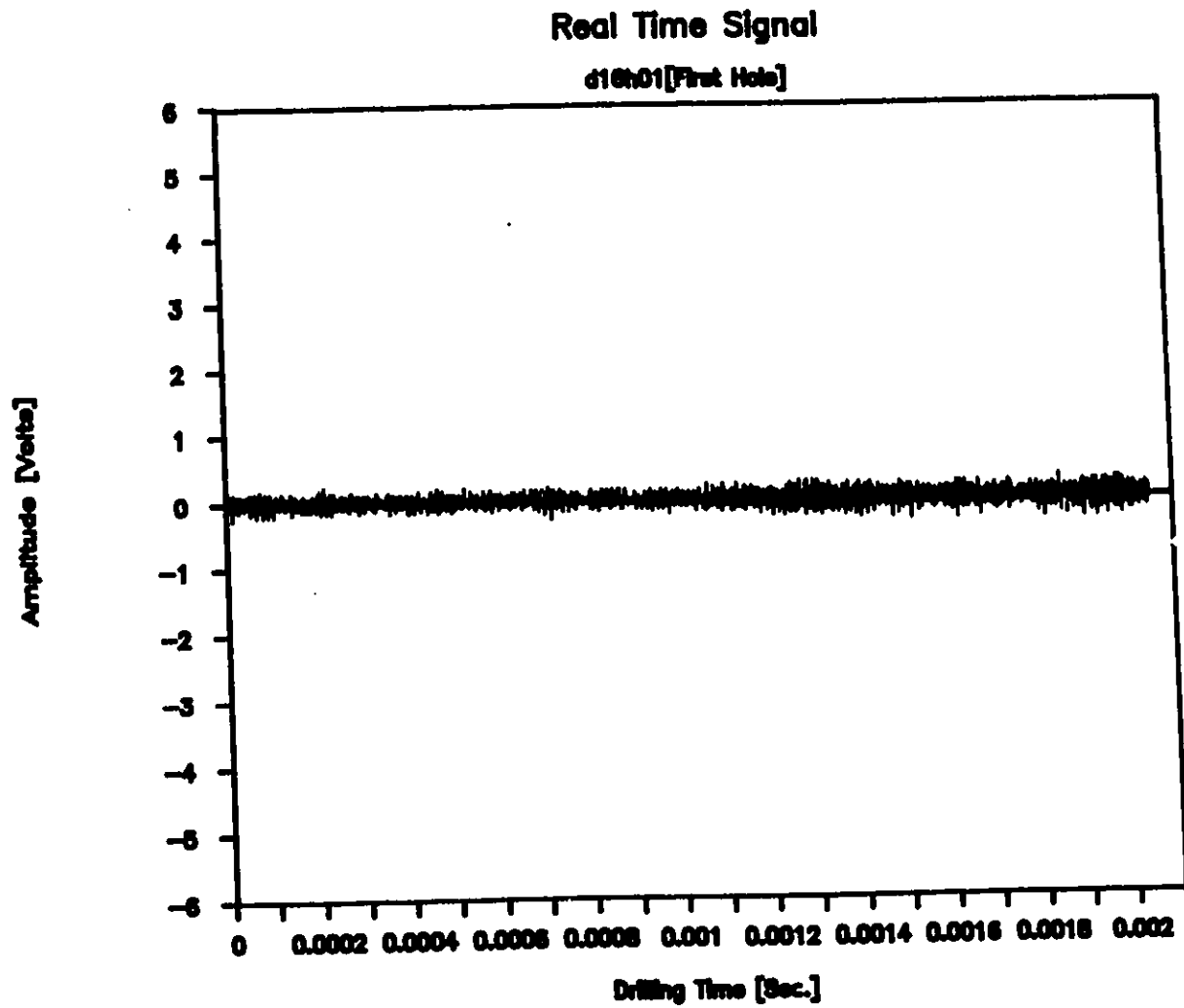


Figure 5.6. Amplitude-time signal from drilling with a sharp drill.

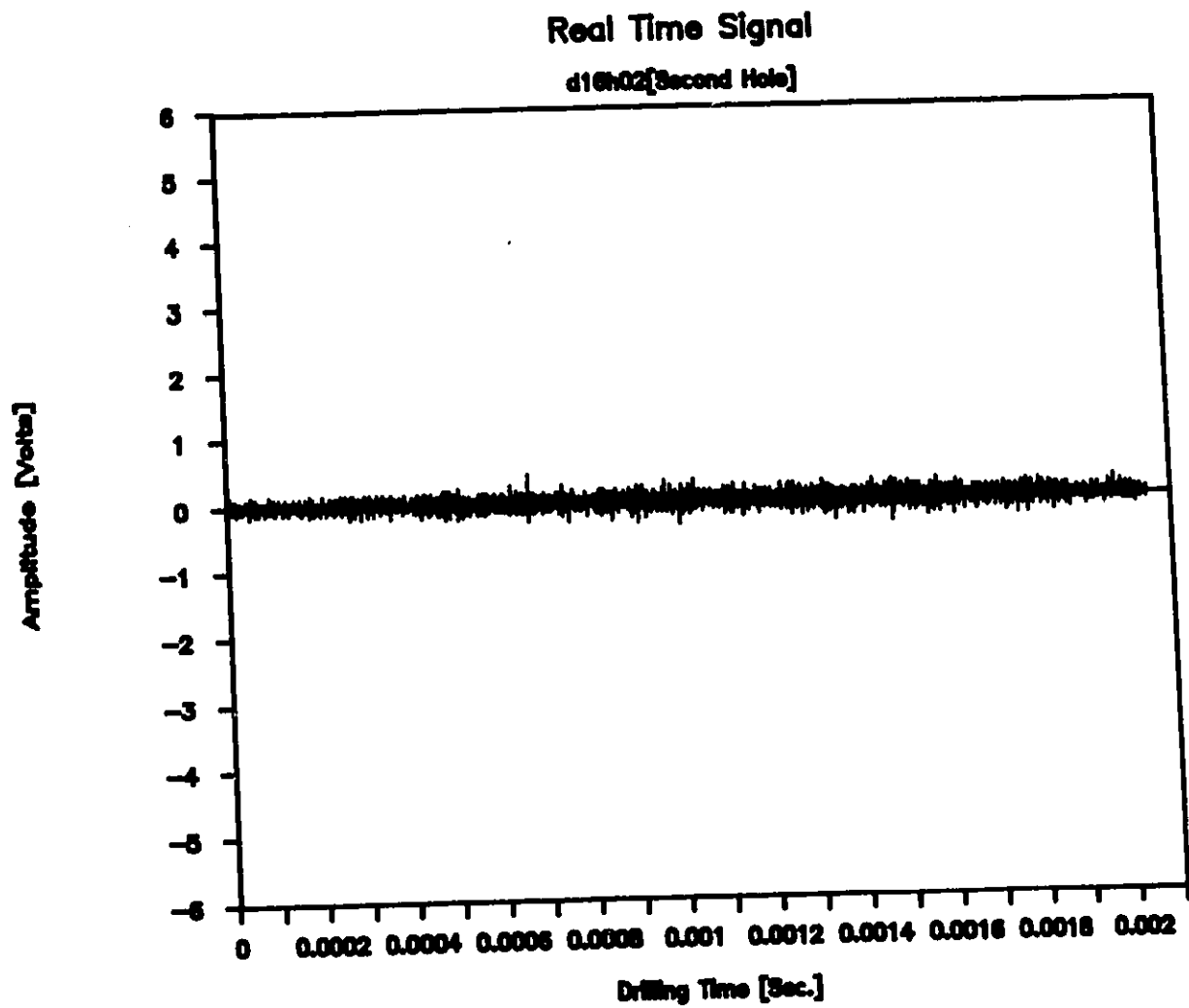


Figure 5.7. Amplitude-time signal from second hole drilling.

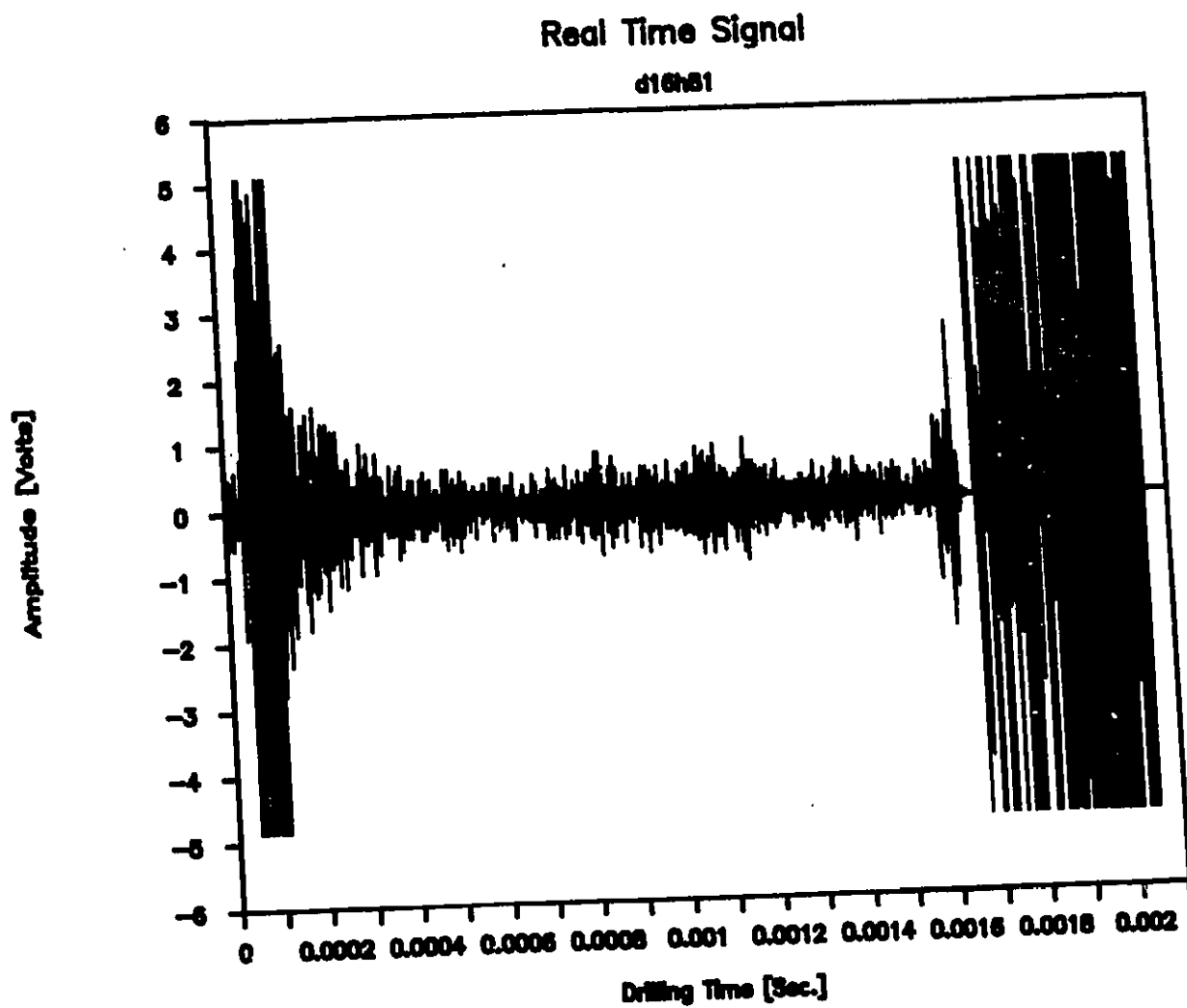


Figure 5.8. Amplitude-time signal from drilling at second last hole.

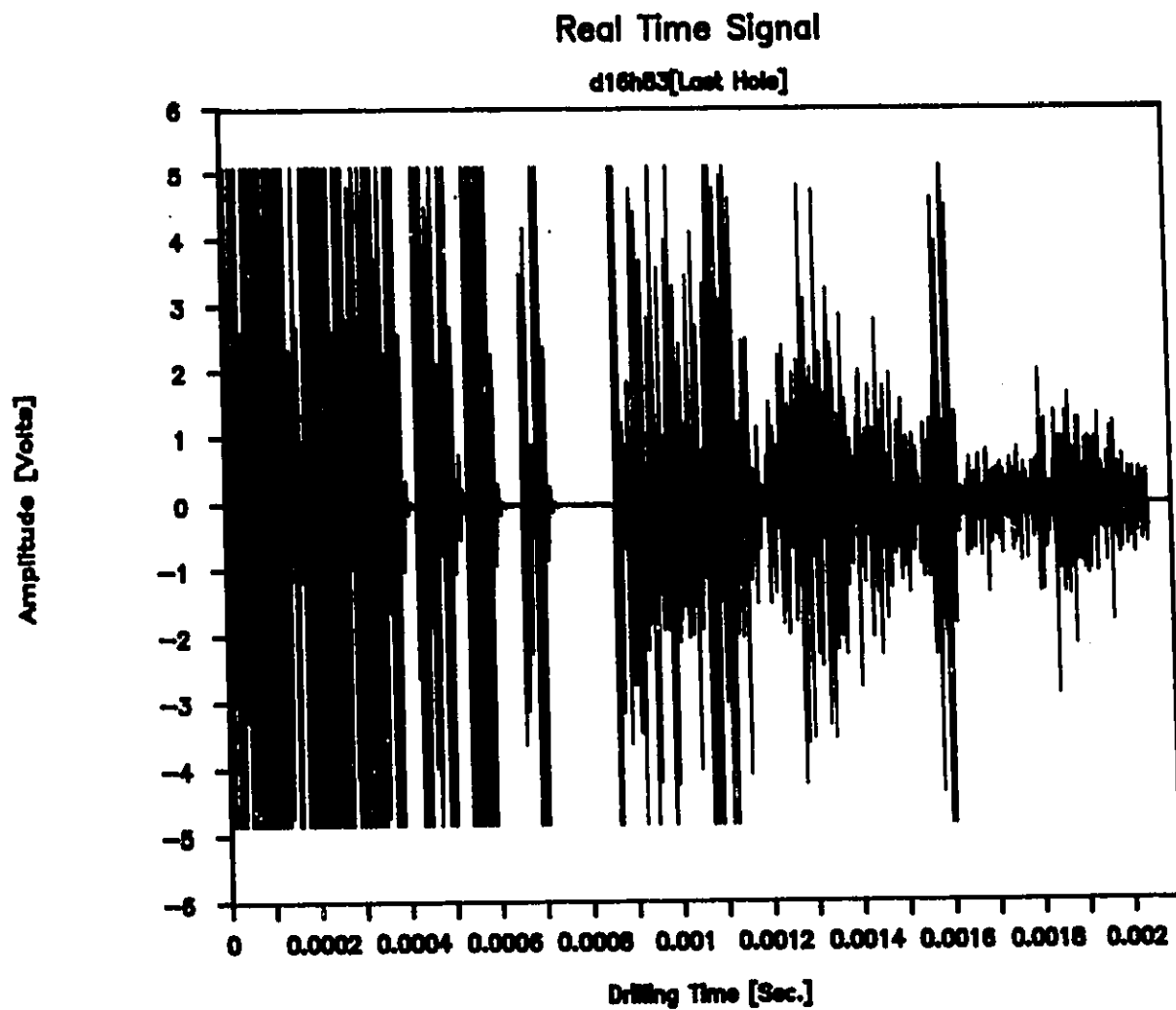


Figure 5.9. Amplitude-time signal from drill when the drill failure is imminent.

as shown in Figures 5.8 and 5.9. The author considers this to be one of the potential parameters to detect drill failure.

5.4.2. AE Count versus Drill Life

A 16 bit pulse counter, installed in an IBM-XT personal computer, was used to count the number of amplitudes which exceeded the pre-set threshold level when drilling. The pulse counts were normalized by dividing the AE counts measured after each drilling by the AE counts at drill failure. Drill life was also normalized as the actual number of drilled holes divided by the total number of holes at drill failure. The resulting normalized pulse counts, defined as data A in graphs 5.10 to 5.24, were plotted against normalized drill life. The best fit curves were drawn as determined by the least square fit to the third degree polynomial.

Two different trends, similar to those previously obtained for drill wear, were observed. In the first case the characteristics consist of three distinct portions, with initially a rapid increase of counts followed by a gradual levelling off or decrease and finally a rapid increase in counts close to failure, as shown in Figures 5.10 to 5.21. In the second case, the curves exhibit a continuous upward trend until drill failure, as shown in Figures 5.22 to 5.24.

In Figures 5.10 to 5.24, the mean value of three consecutive normalized AE counts, which were calculated using equation (38),

and defined as controlled data B, are also plotted against normalized drill life (plotted in red colour). It was an attempt at obtaining a better correlation of the AE counts against normalized drill life, particularly when the warning point of the drill condition with the change of slope is investigated, as shown in Figure 6.3.

$$MCNT_i = \frac{1}{3} \sum_{j=i-1}^{i+1} ACNT_j, \text{ for } i=2,3,4\dots n-1. \quad (38)$$

where MCNT is a mean value of normalized AE count,

ACNT is a normalized AE count,

$MCNT_i = ACNT_i$ and

$MCNT_n = ACNT_n$.

A very close curvefit was observed in both normal AE count (shown in black) and three point mean AE count plotting (shown in red) in Figures from 5.10 to 5.24. However, better coefficients of correlation were obtained when the three point mean AE count was used for plotting.

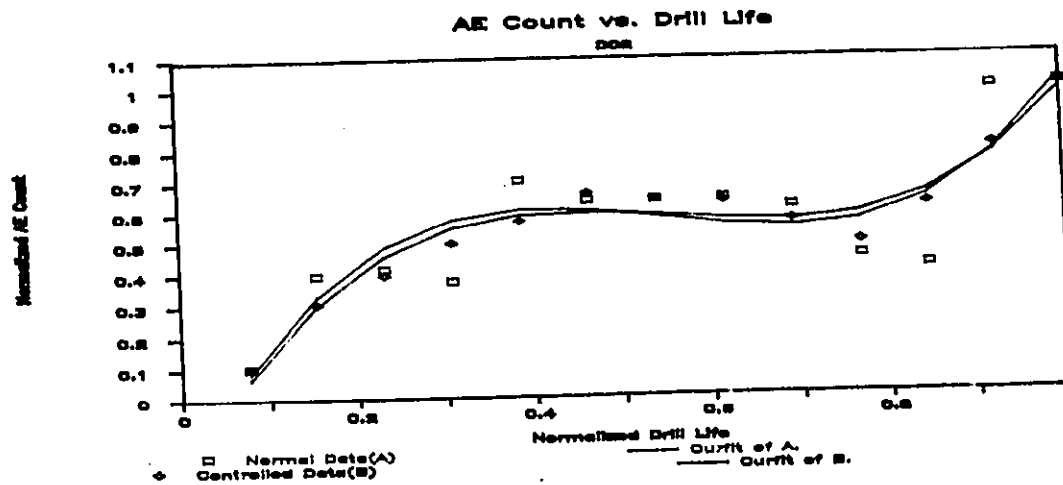


Figure 5.10. AE count vs. drill life and their curvefit, type I.

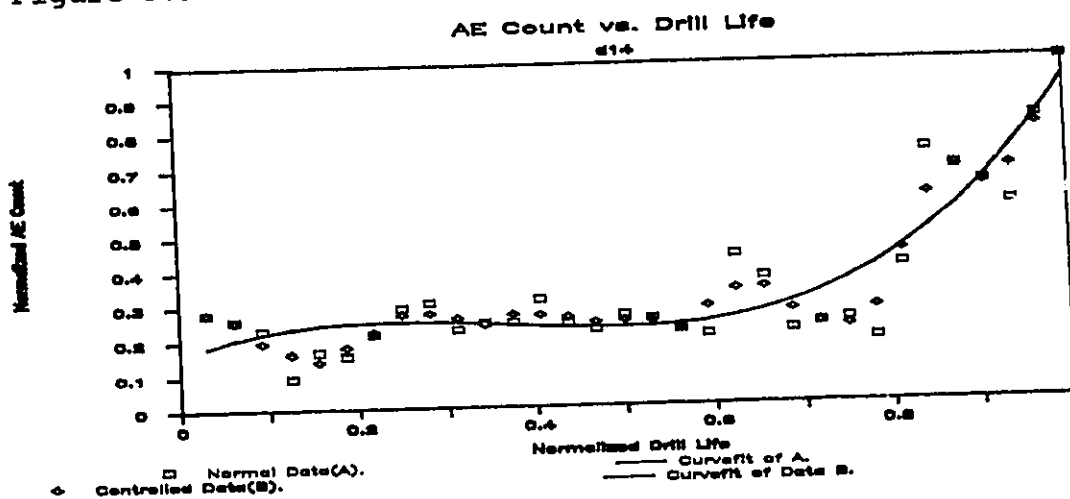


Figure 5.11. AE count vs. drill life and their curvefit, type I.

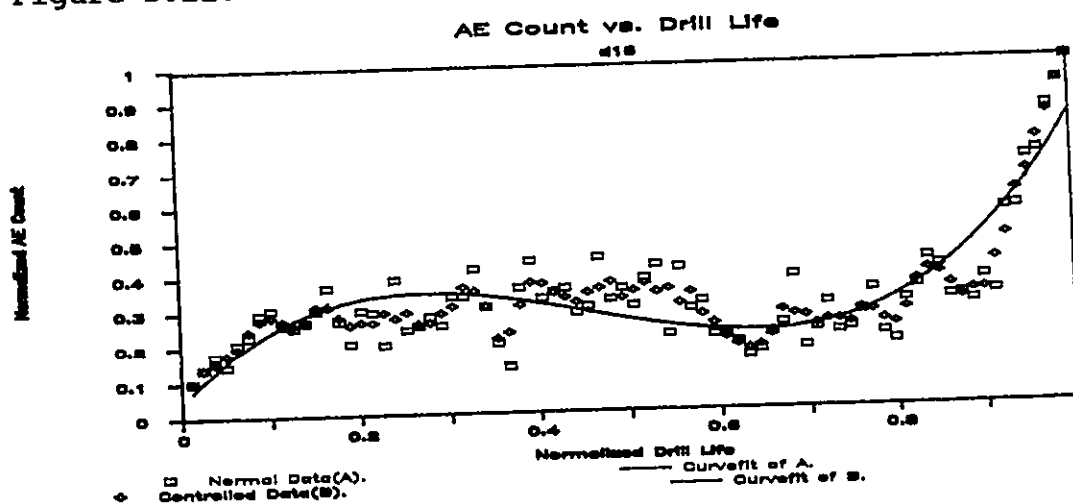


Figure 5.12. AE count vs. drill life and their curvefit, type I.

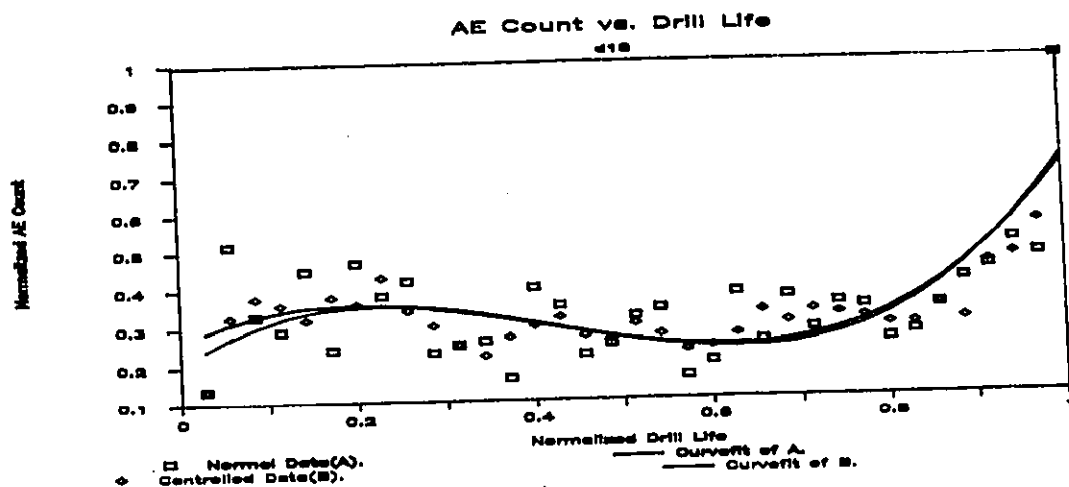


Figure 5.13. AE count vs. drill life and their curvefit, type I.

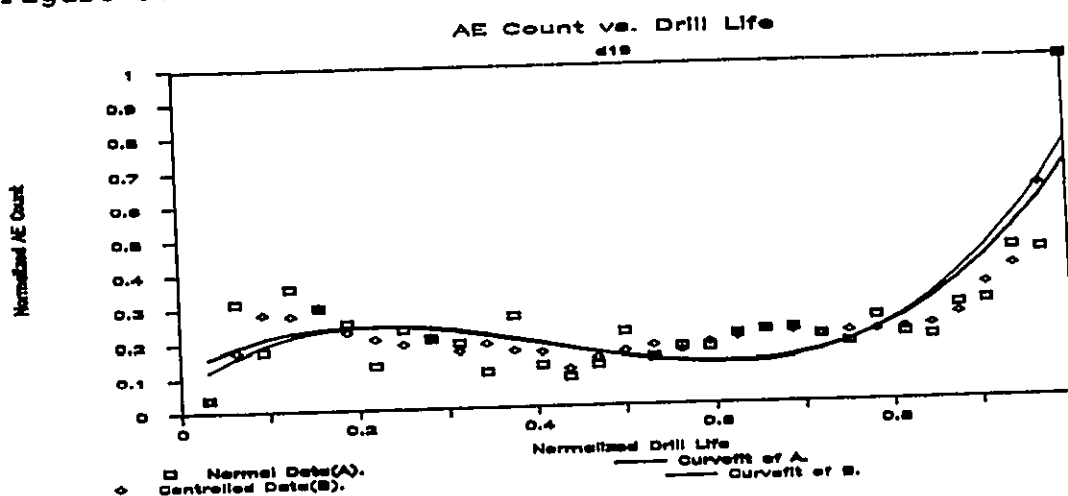


Figure 5.14. AE count vs. drill life and their curvefit, type I.

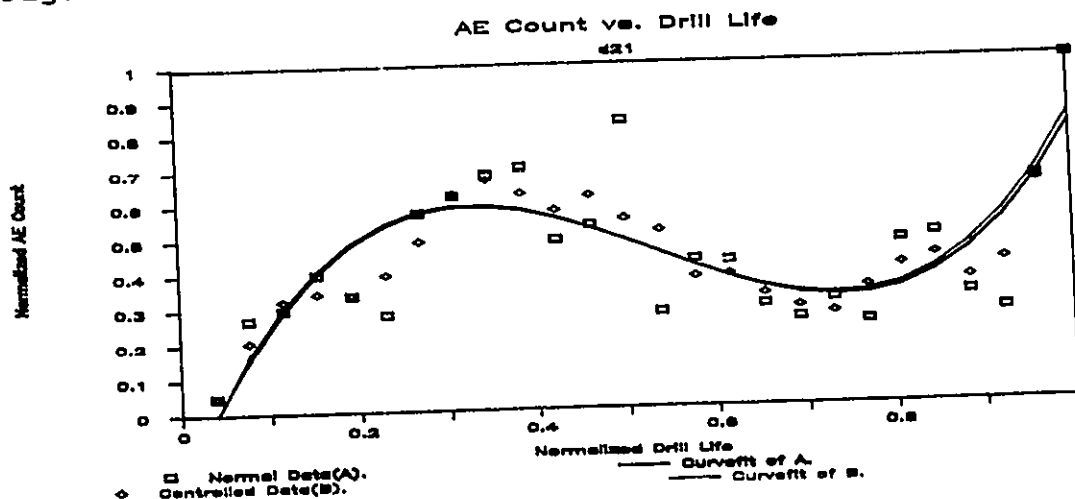


Figure 5.15. AE count vs. drill life and their curvefit, type I.

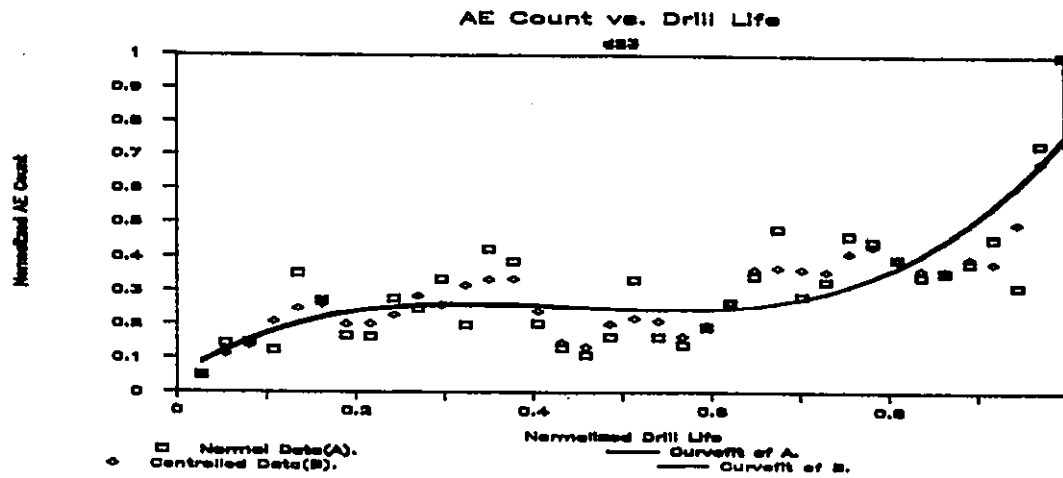


Figure 5.16. AE count vs. drill life and their curvefit, type I.

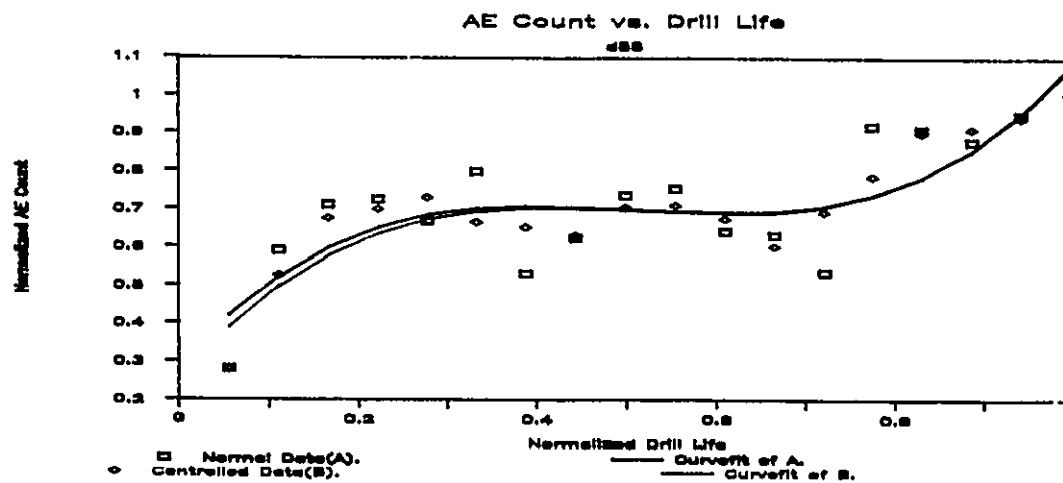


Figure 5.17. AE count vs. drill life and their curvefit, type I.

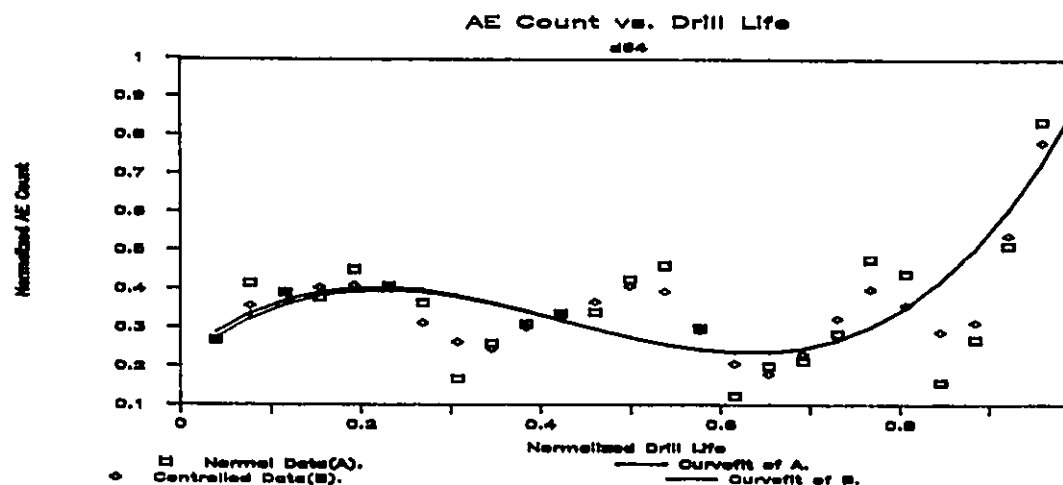


Figure 5.18. AE count vs. drill life and their curvefit, type I.

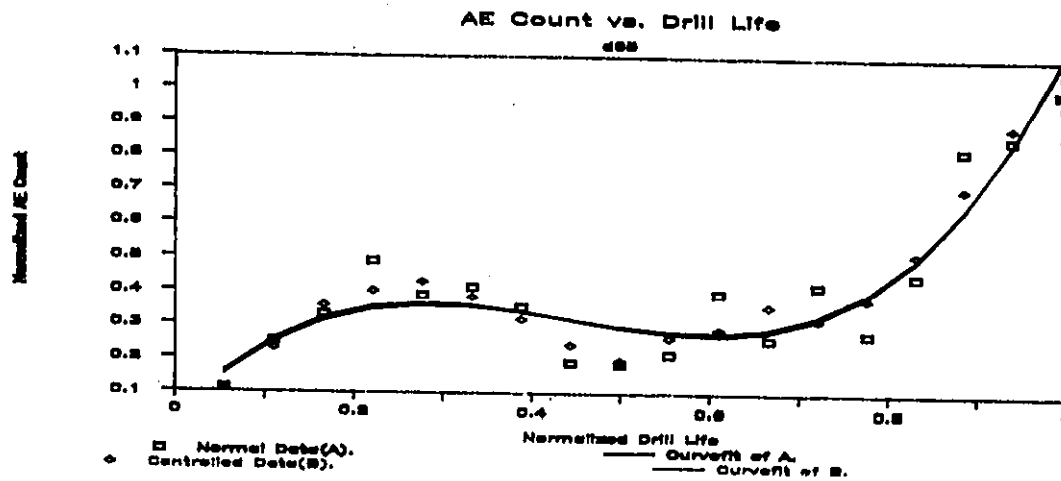


Figure 5.20. AE count vs. drill life and their curvefit, type I.

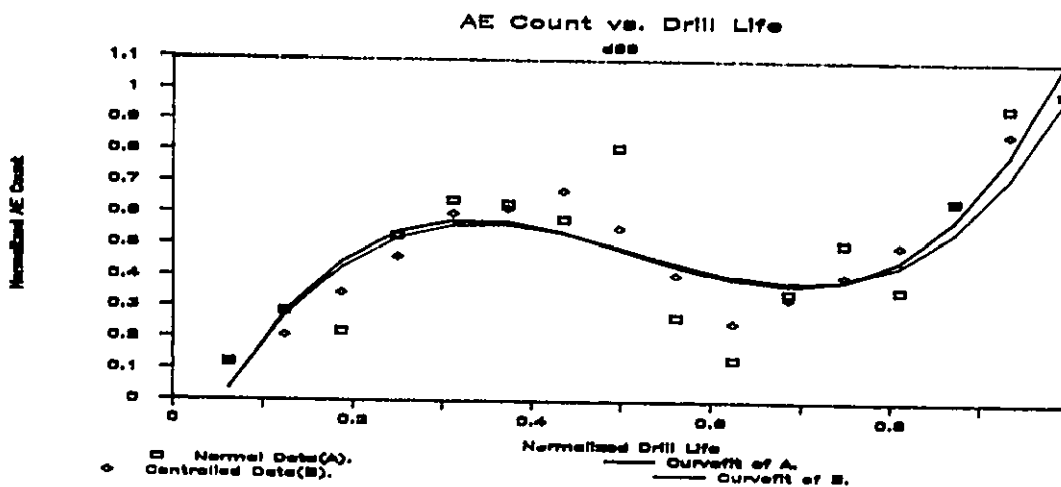


Figure 5.20. AE count vs. drill life and their curvefit, type I.

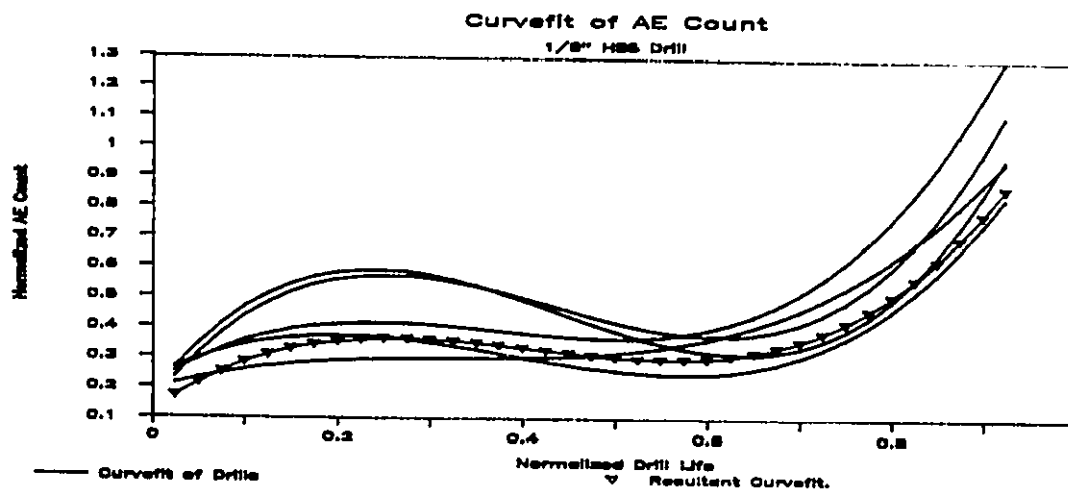


Figure 5.21. Curvefit groups of AE count vs. drill life and their resultant curve.

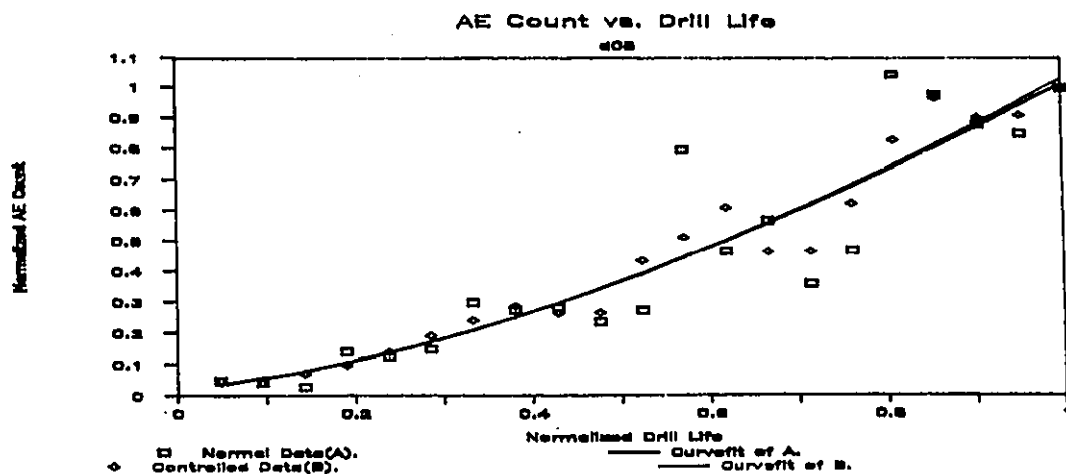


Figure 5.22. AE count vs. drill life and their curvefit, type II.

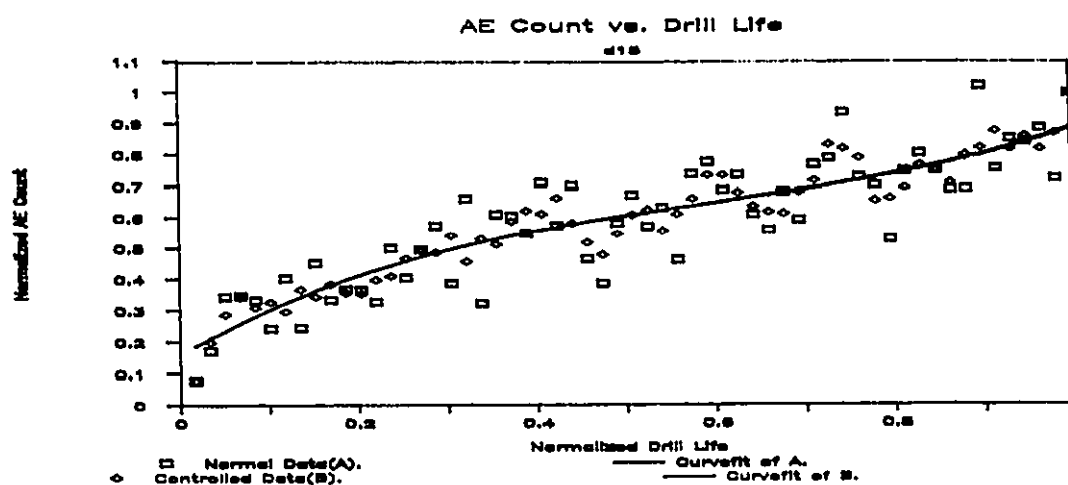


Figure 5.23. AE count vs. drill life and their curvefit, type II.

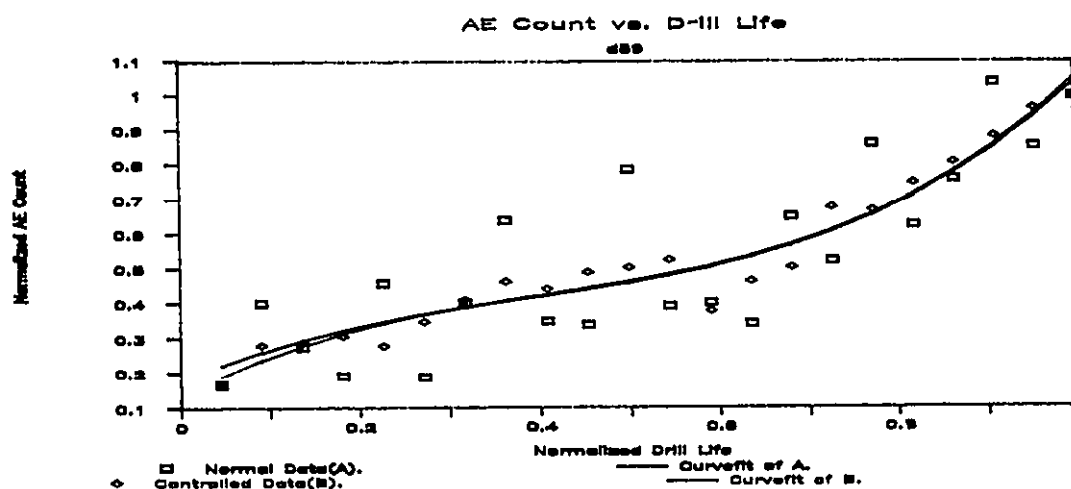


Figure 5.24. AE count vs. drill life and their curvefit, type II.

5.4.3. Drill Wear and AE Count

Comparisons were made between drill wear and AE counts to examine the validity of the results. The drill wear was normalized by dividing the wear measured after each drilling by the total accumulated wear at drill failure. Two types of similar trends were again observed. For the first type, as shown in Figure 5.25, both normalized drill wear and AE count increased rapidly in the first stage of drilling. This was followed by a levelling off section for wear and a slight decrease for the AE Count. Finally both, wear and AE count, increased rapidly until drill failure.

The second type of trend for drill wear and AE count change, which only shows two distinct stages of drilling, was also observed as shown in Figure 5.26.

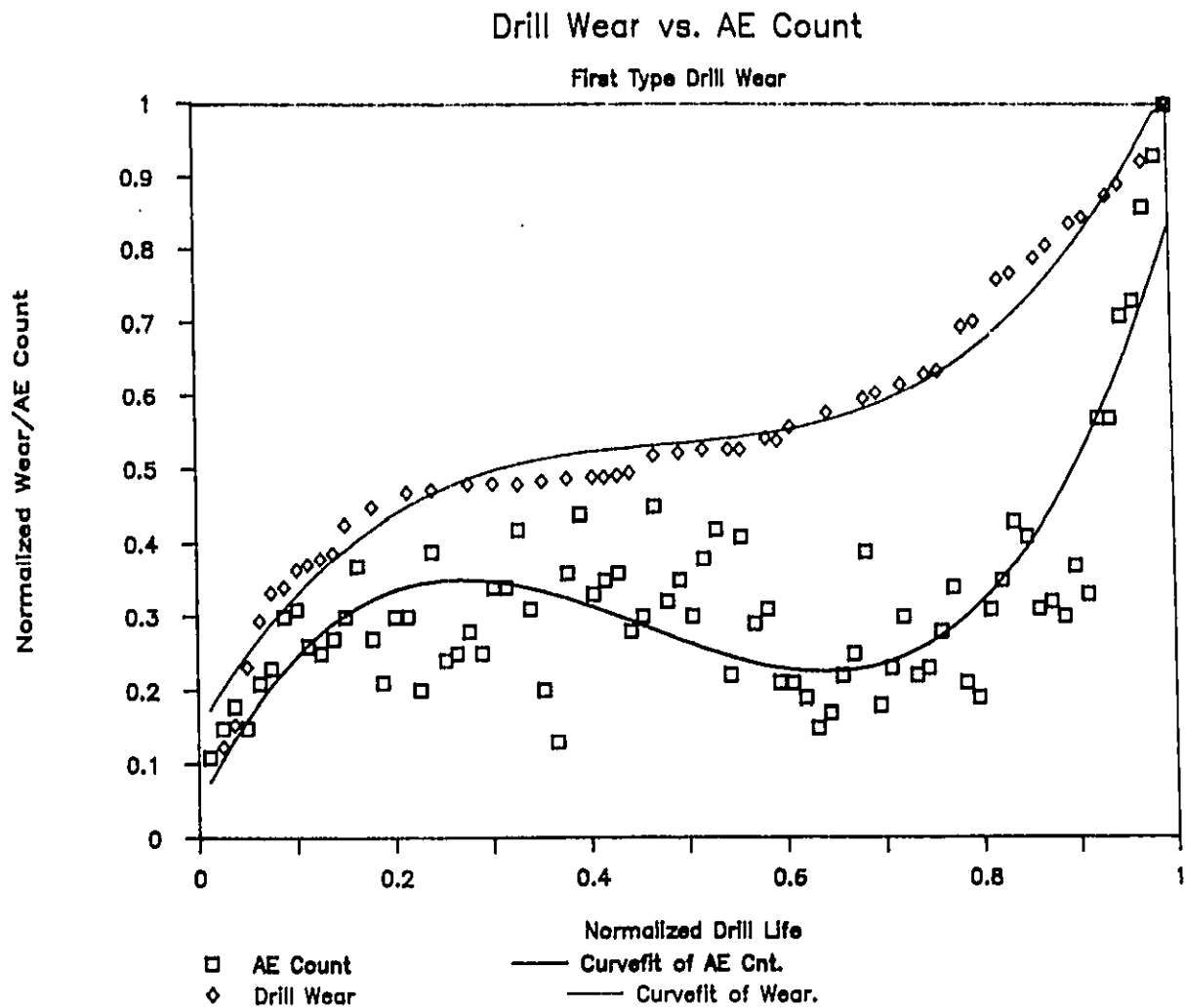


Figure 5.25. Comparison of response curve of drill wear and AE count - type I.

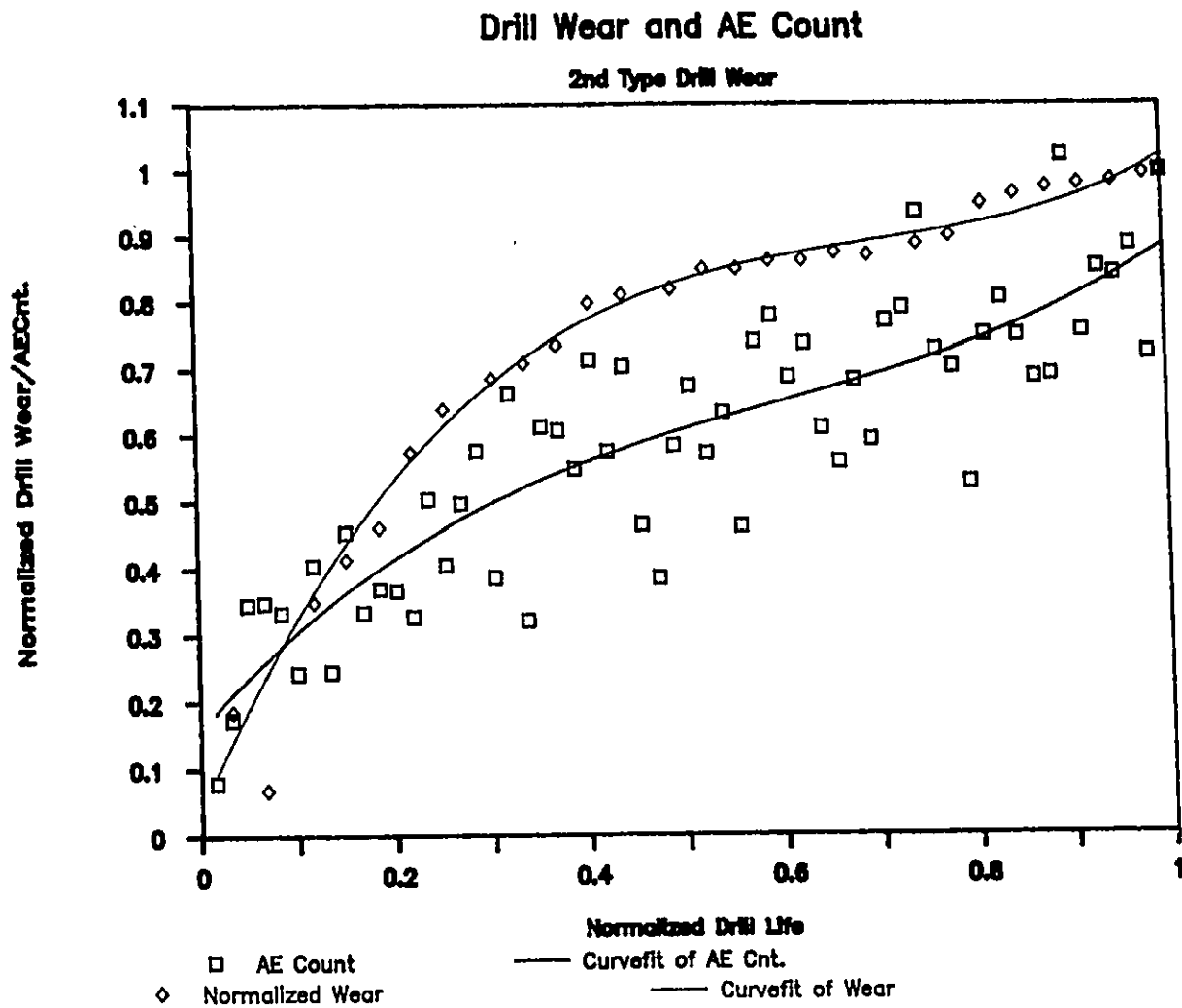


Figure 5.26. Comparison of response curve of drill wear and AE count - type II.

5.4.4. TRMS (True Root Mean Square) versus Drill Life

Since the strain energy from the AE signal is proportional to the square of the RMS value[91], the TRMS (true root mean square) was employed as one of the parameters which would be able to indicate the drill situation during drilling. The TRMS was measured for the whole period of drilling one hole, while for the source of the previous statistical descriptors, only one sample of maximum duration of 0.016 seconds, as captured by the digital oscilloscope, was used.

Figure 5.27 shows the output of TRMS against effectively the depth of hole for the whole period of one hole drilling. Generally, not much change of the TRMS value was noticed when the drilling was started, however, it increased with the depth of drilling. The TRMS of three holes, with a sharp drill, 40 % worn drill and when failure was imminent, were also compared. As shown in Figure 5.27, the worn drill resulted in higher TRMS compared to the sharp drill, particularly when drill failure was imminent.

The TRMS from initial drilling to the drill failure are plotted against the number of drilled holes, as shown in Figure 5.28. One group of peaks in the graph represents the change of TRMS as depth increases from one hole drilling and forty six holes are compared.

Three statistical parameters, maximum, average and standard deviation of TRMS, were also studied. Correlations of those parameters from initial drilling to drill failure against

normalized drill life were made with the use of a third degree polynomial curvefit.

Two types of curves, which are similar to those with the AE counts, were observed. In the first case, initially the TRMS increased rapidly followed by a gradual levelling off or decrease and finally a rapid increase in values close to failure, as shown in Figure 5.29 and defined as type I. In the second case, the curves exhibit a continuous upward trend until drill failure, as shown in Figures 5.30 and defined as type II.

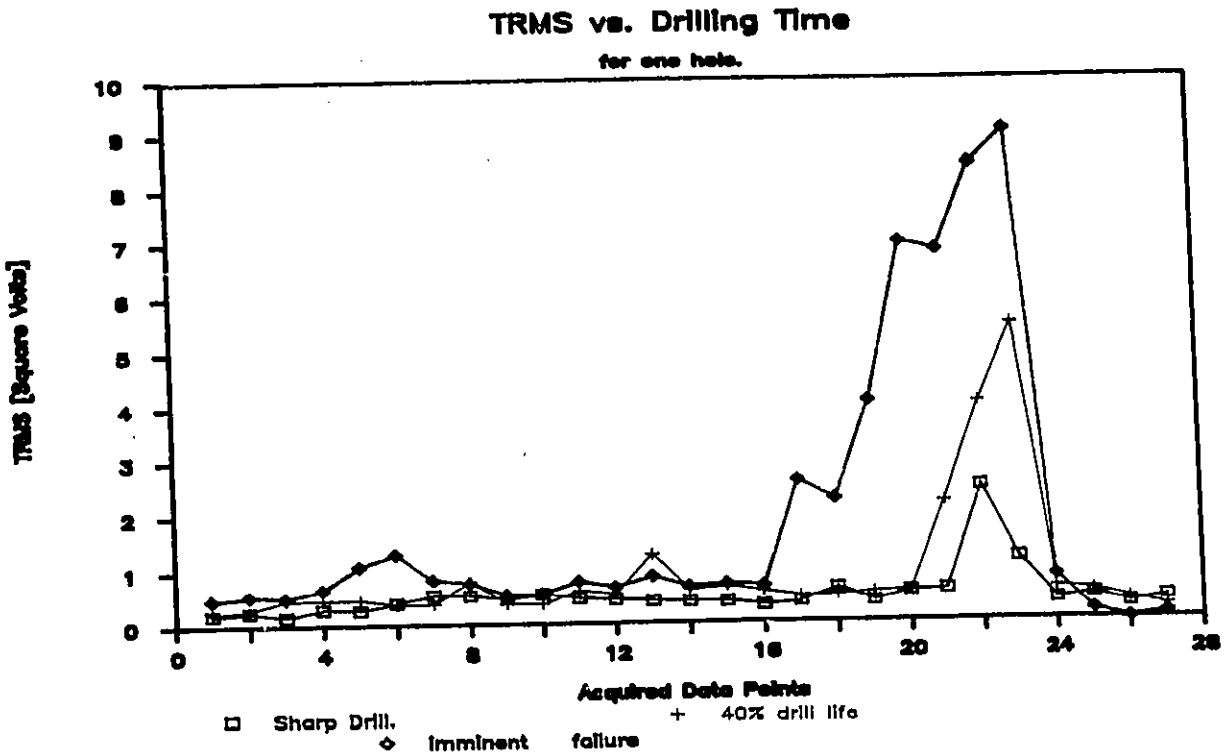


Figure 5.27. Output of TRMS during one hole drilling.

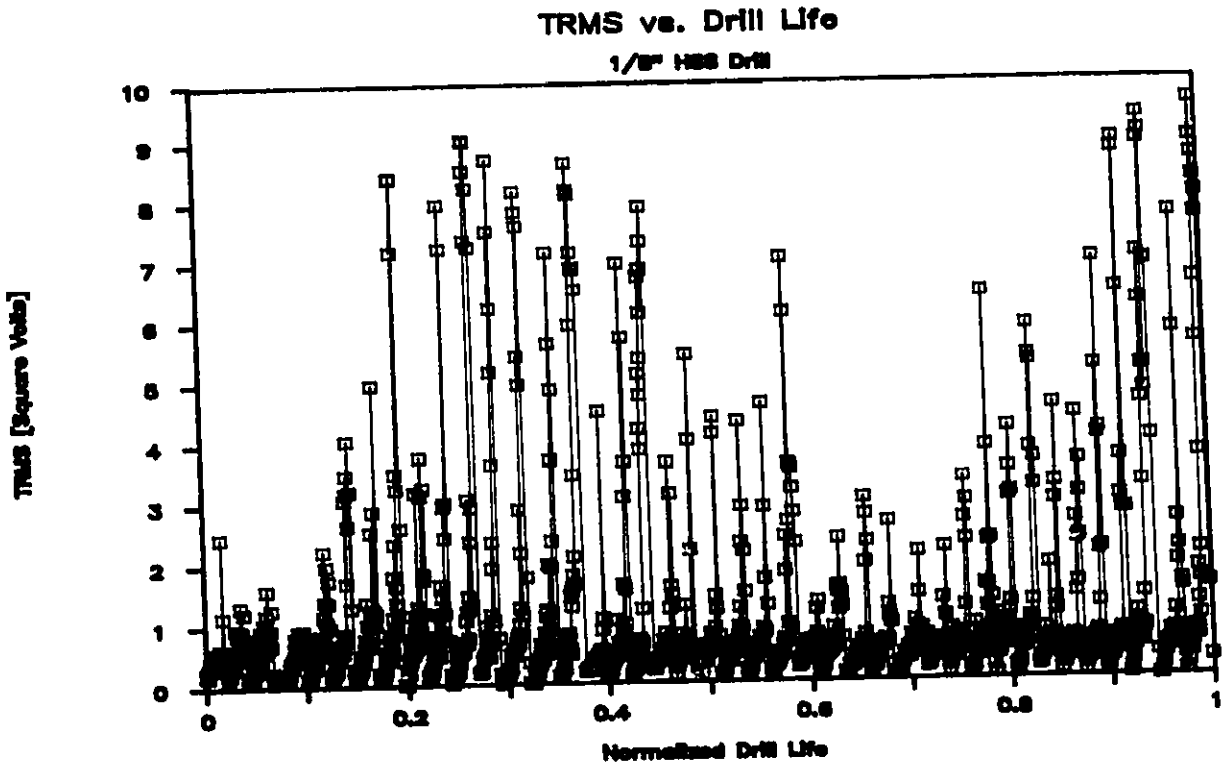


Figure 5.28. TRMS of drilling from first hole with a sharp drill to the drill failure.

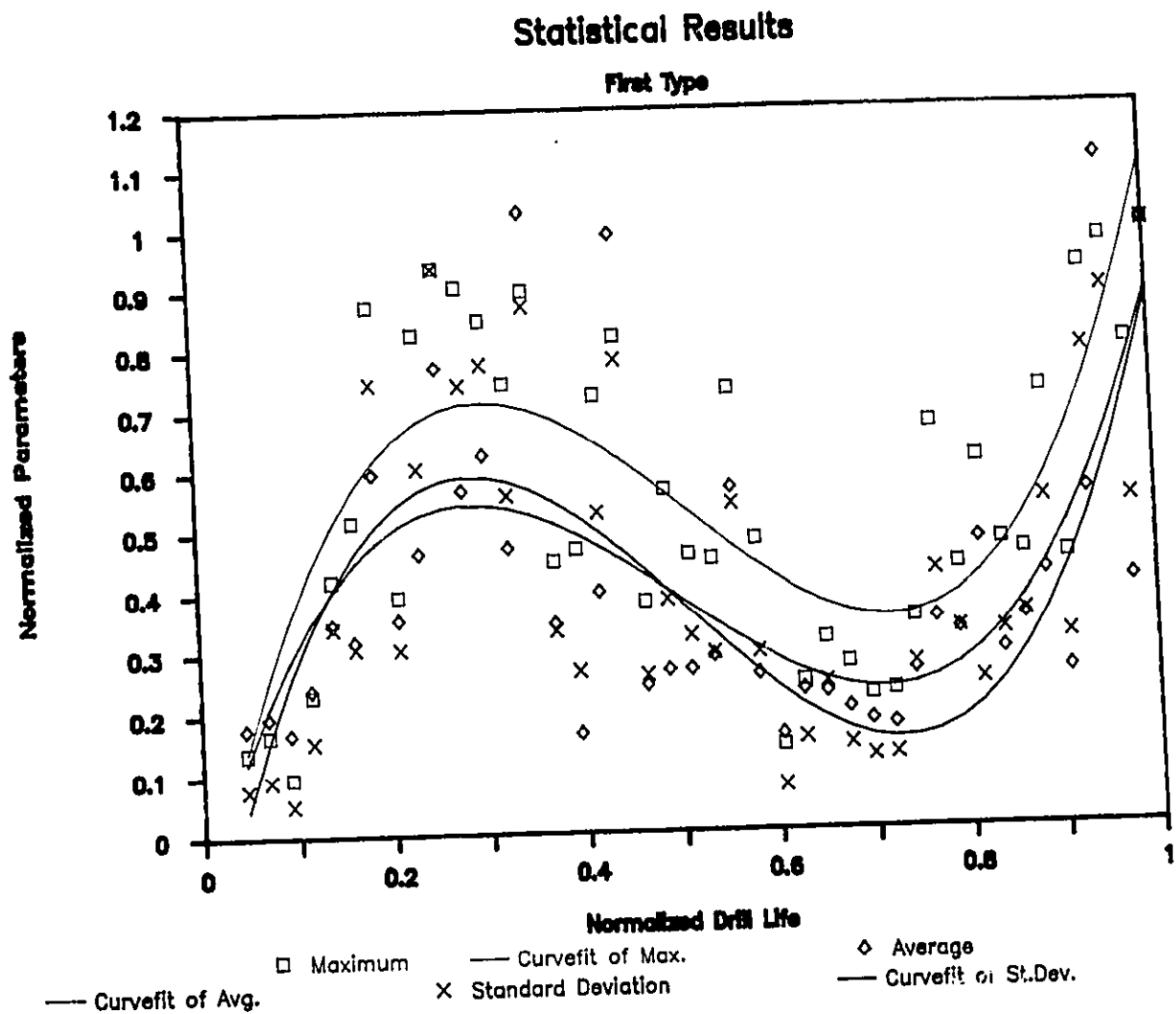


Figure 5.29. Statistical results of TRMS value with respect to drill life - Type I.

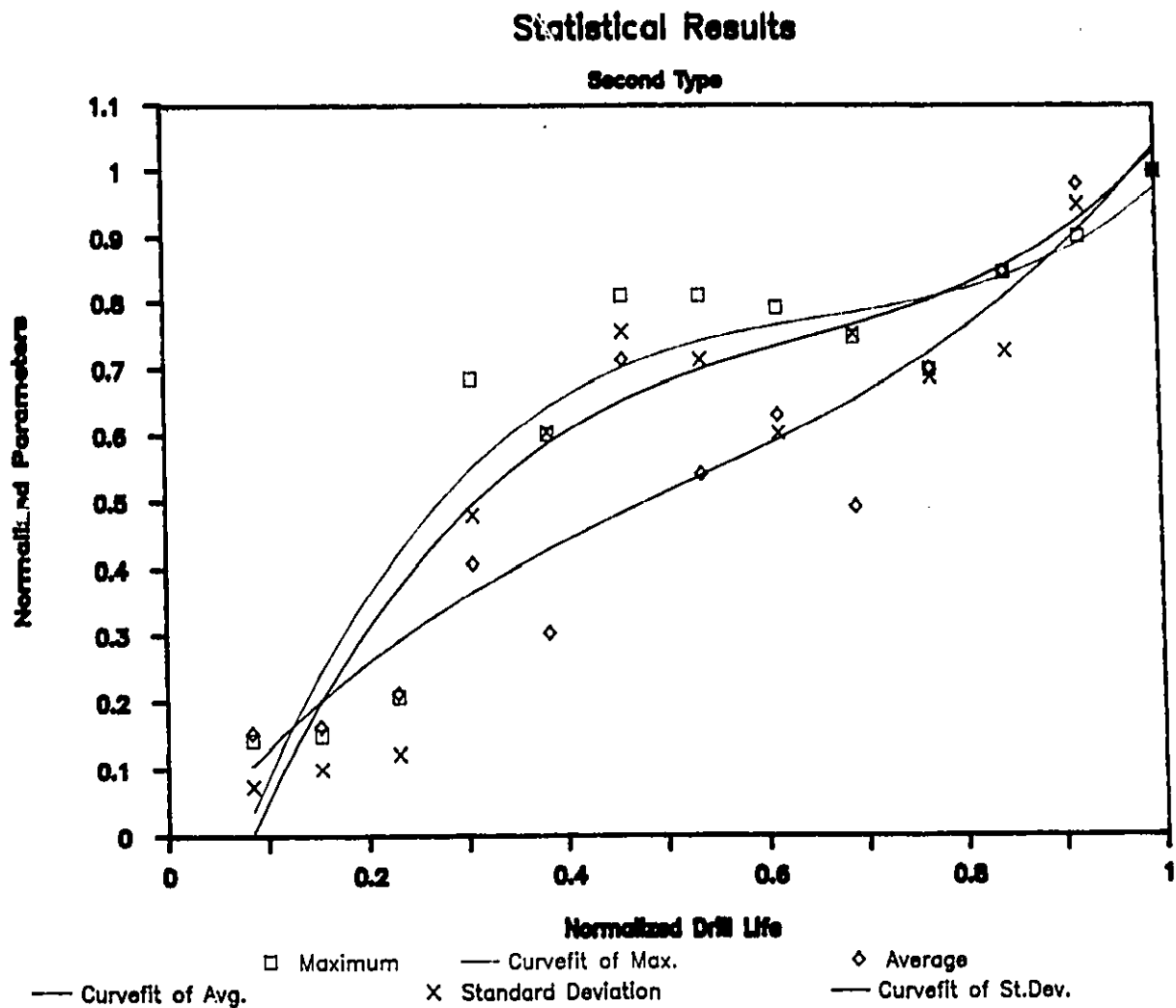


Figure 5.30. Statistical results of TRMS value with respect to drill life - Type II.

5.4.5. Statistical Analyses

To avoid time consuming data evaluation by comparing amplitudes of the time series data from initial drilling to the failure, statistical parameters were employed. As described in chapter 4 on Data Analysis, 16K AE points were captured by the digital oscilloscope during drilling, and were stored in the computer. This data was then grouped, as shown in Figure 5.31, to get the advantage of faster statistical computation. Five statistical parameters were then derived from the amplitude distributions. The changes with normalized drill life of amplitude distribution, RMS, standard deviations, mean, skewness, and kurtosis were investigated.

5.4.5.1. Amplitude Distributions

As is depicted in Figures 5.6, 5.7, 5.8 and 5.9, the amplitudes of AE signals with the sharp drills are low and consistent while with the worn drill they are high and fluctuating. However, the observation of time-amplitude signals from new drill to failure is time consuming. Hence, the time-amplitude signal changes with the increase of drilled holes were observed by means of amplitude distribution of grouped data. The acquired AE data with a new drill were grouped to a certain number(eg., 100 groups) of same interval amplitudes, as shown in Figure 5.31, and the occurrences of each grouped amplitude were

plotted. The procedure was repeated for the data from initial drilling to that of drill failure.

A typical graph of the number of occurrences versus grouped amplitude of AE signal for one set of drilling data is shown in Figures 5.32 and 5.33. In the graph, the number of the drilled holes at failure was defined as 100 percent of a drill life, and the proportion of the number of actual drilled holes to the number of drilled holes at failure was defined as percentage of drill life.

As shown in the graphs, most of the amplitudes from initial drilling are concentrated in the low value with a sharp bell shape, and then gradually, as the number of drilled holes increases, the amplitude distributions change to wide bell shape until 55 percent of the drill life. After that, the amplitudes gradually concentrate at the low value with a relatively sharp bell shape again until 75 percent of drill life. Finally the amplitude distribution becomes practically flat near imminent drill failure.

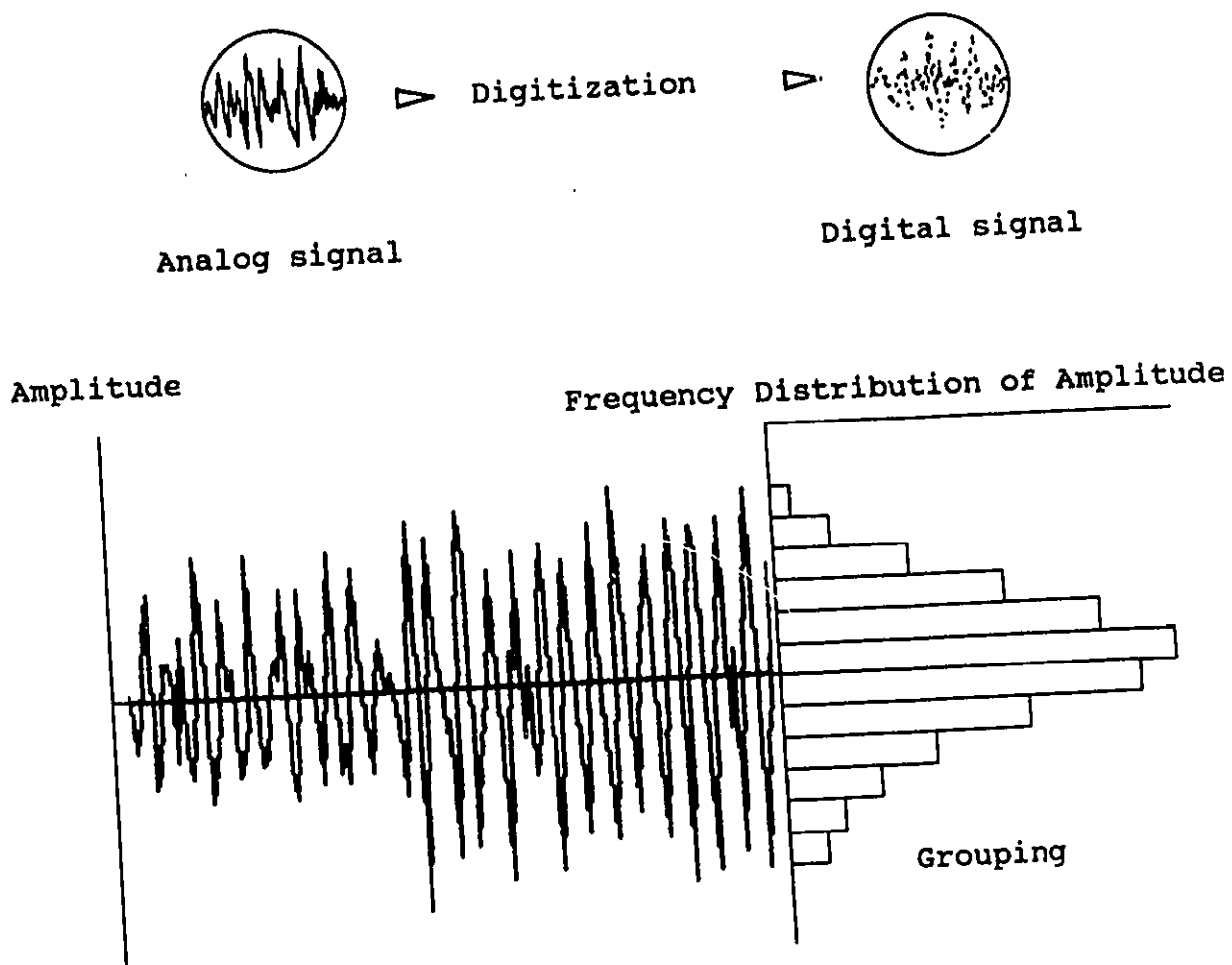


Figure 5.31. The schematic diagram of digitization of analog signal and data grouping process.

Amplitude Distribution

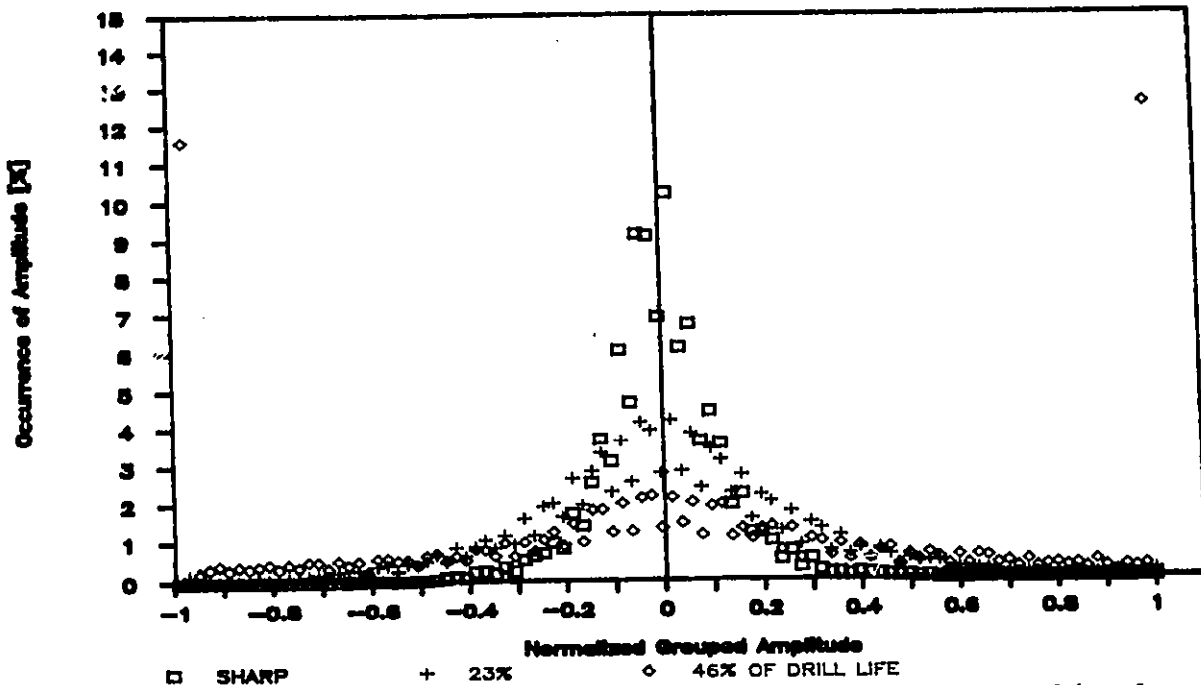


Figure 5.32. Number of occurrences of grouped amplitude during drilling.

Amplitude Distribution

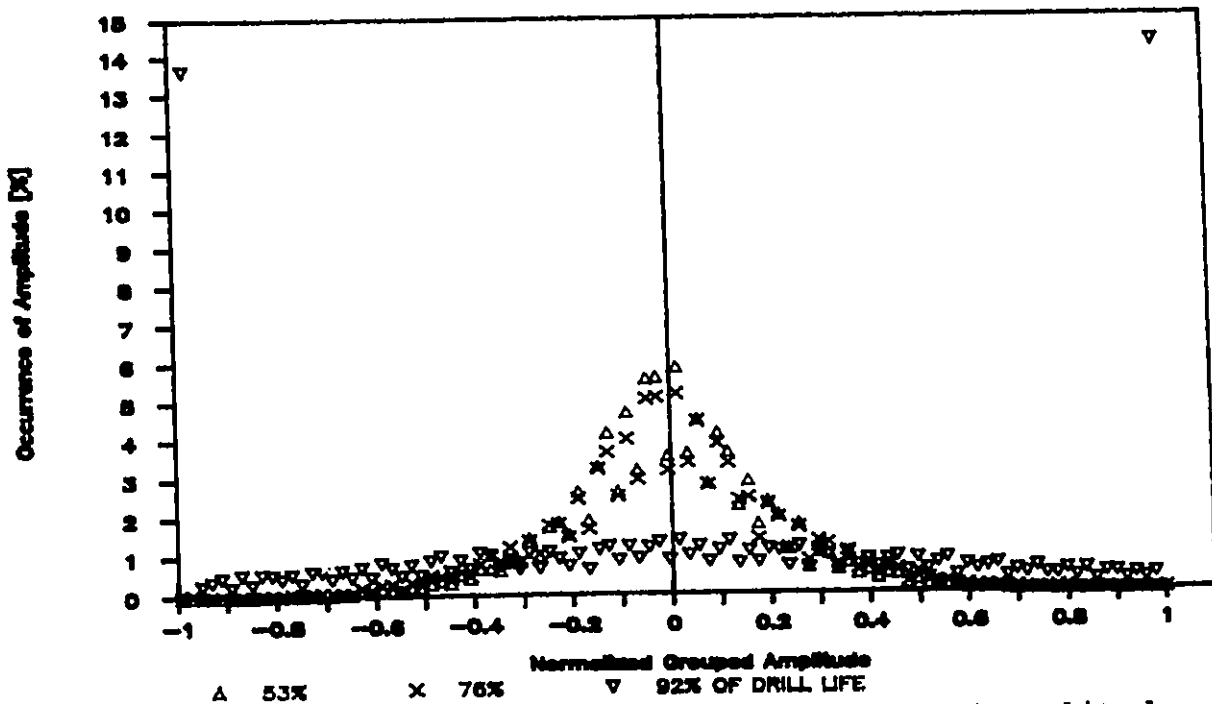


Figure 5.33. Number of occurrences of grouped amplitude during drilling.

5.4.5.2. RMS and Standard Deviation

The RMS and standard deviations obtained by using the 16K data points were plotted against normalized drill life, and typical plots are shown in Figure 5.34. Initially the RMS values are generally low with sudden increases when failure is imminent. A similar trend was observed when standard deviation was plotted against drill life, as shown in Figure 5.35. However, a useful condition monitoring trend is not consistently present.

The inadequacy of these results is due to three difficulties. Firstly, the visual observation and control of the high frequency signals on the oscilloscope was impossible since their reside time on the screen was too short. Therefore, it was not possible to capture the exact set of data as intended by the operator. Secondly, the storing capacity of the time period signal to the computer diskette for further analysis was a maximum of 0.016 seconds for one hole because of the limited memory capacity of the digital oscilloscope and the required transfer time to the computer. In other words, the captured data on the oscilloscope could represent only a particular portion of the drilling sequence, i.e., chip breakage, rubbing, etc., as shown in Figures 5.36 and 5.51. Therefore, one set of data may not be comparable to another one, which may include different events during drilling. Finally, it was impossible to capture the data at exactly the same depth of drilling and the AE signals are dependent on the depth of drilled hole.

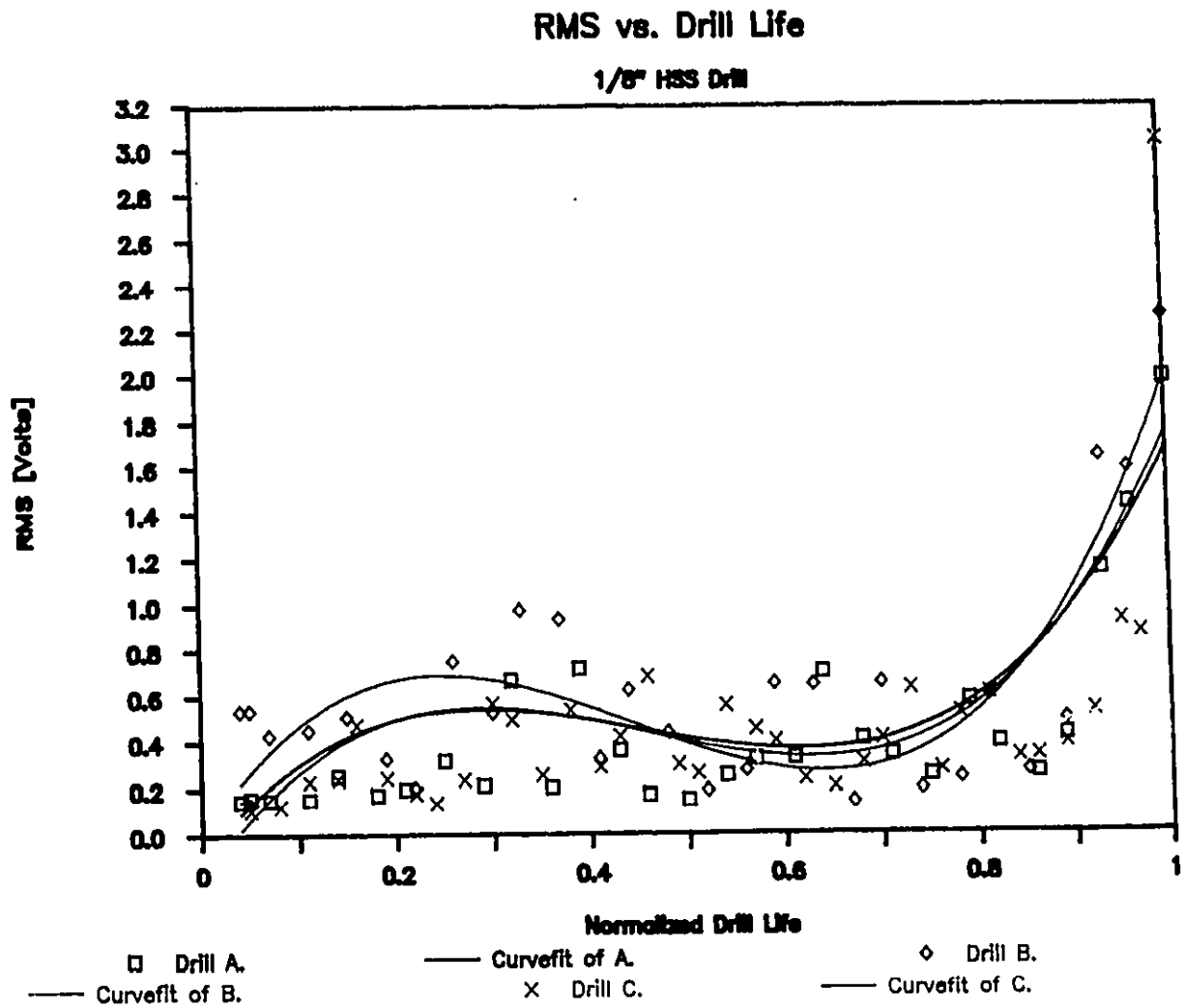


Figure 5.34. RMS of AE signal versus normalized drill life and their curvefit.

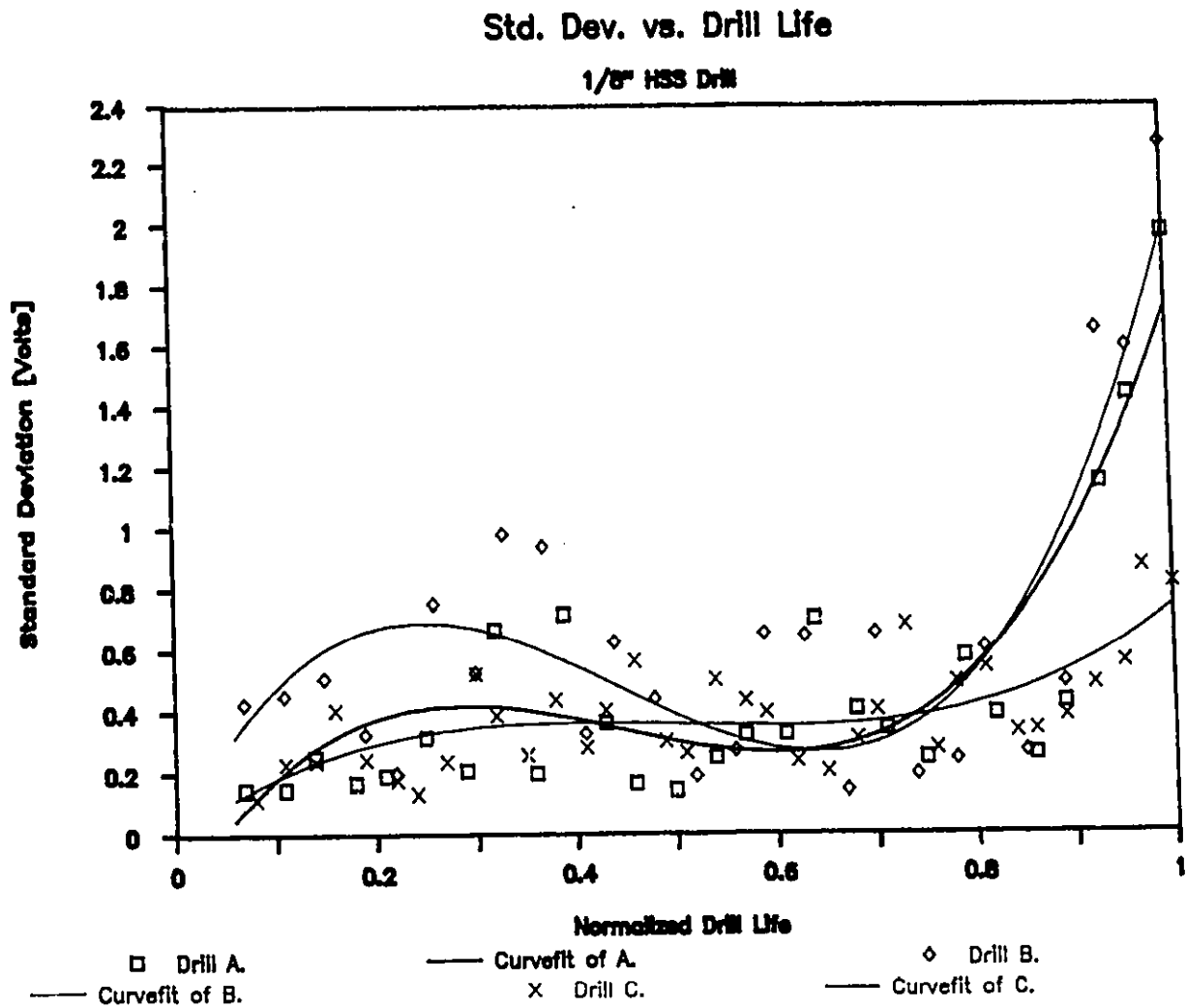


Figure 5.35. Standard deviation of AE signal versus drill life and their curvefit.

5.4.5.3. RMS of Controlled Time Series Data

As it was stated in the previous section, the AE data exhibits large variations of the signal, which is assumed to be due to different events during drilling, as shown in Figure 5.36. In an effort to make these data comparable to each other, the time-series signal was broken into several sections and zoomed, as shown in Figures 5.37 to 5.39. Both results of the RMS, one obtained from 16K data points and the other from the grouped data, are compared. The general trend obtained from both procedures indicates that the signal amplitude increased initially, then decreased, and finally, towards the drill failure, it increased rapidly to a high magnitude, as shown in Figure 5.40, but a better correlation is obtained with the grouping method. However, the grouping method is very time consuming and requires judgment for the selection of the right portion of the data segment such that good comparability is achieved. Although much time was spent on this method, because the results did not exhibit good repeatability, this procedure was not considered to be a useful method of monitoring the drill condition. The required computer software would be too complex and the procedure too slow for most practical applications.

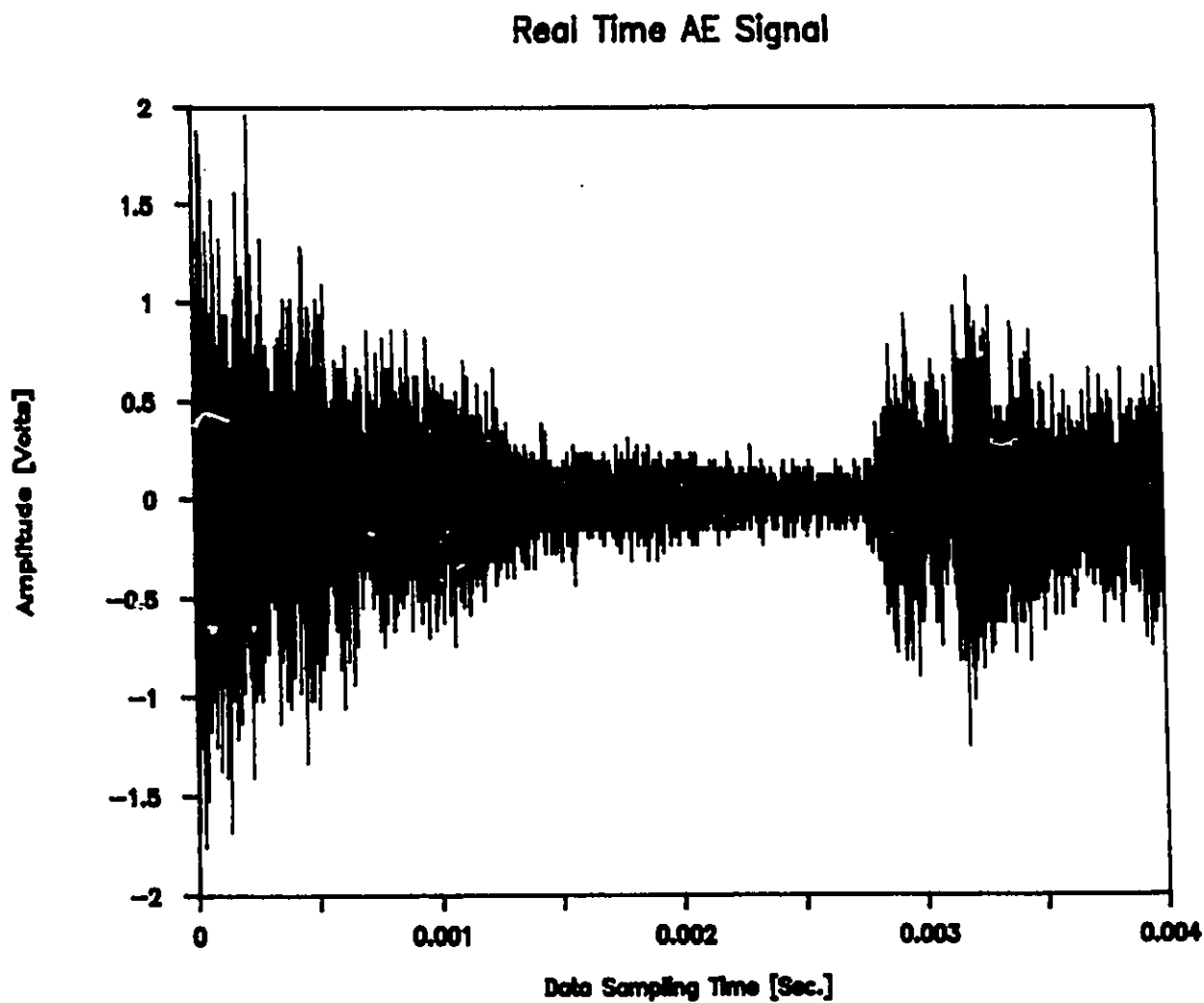
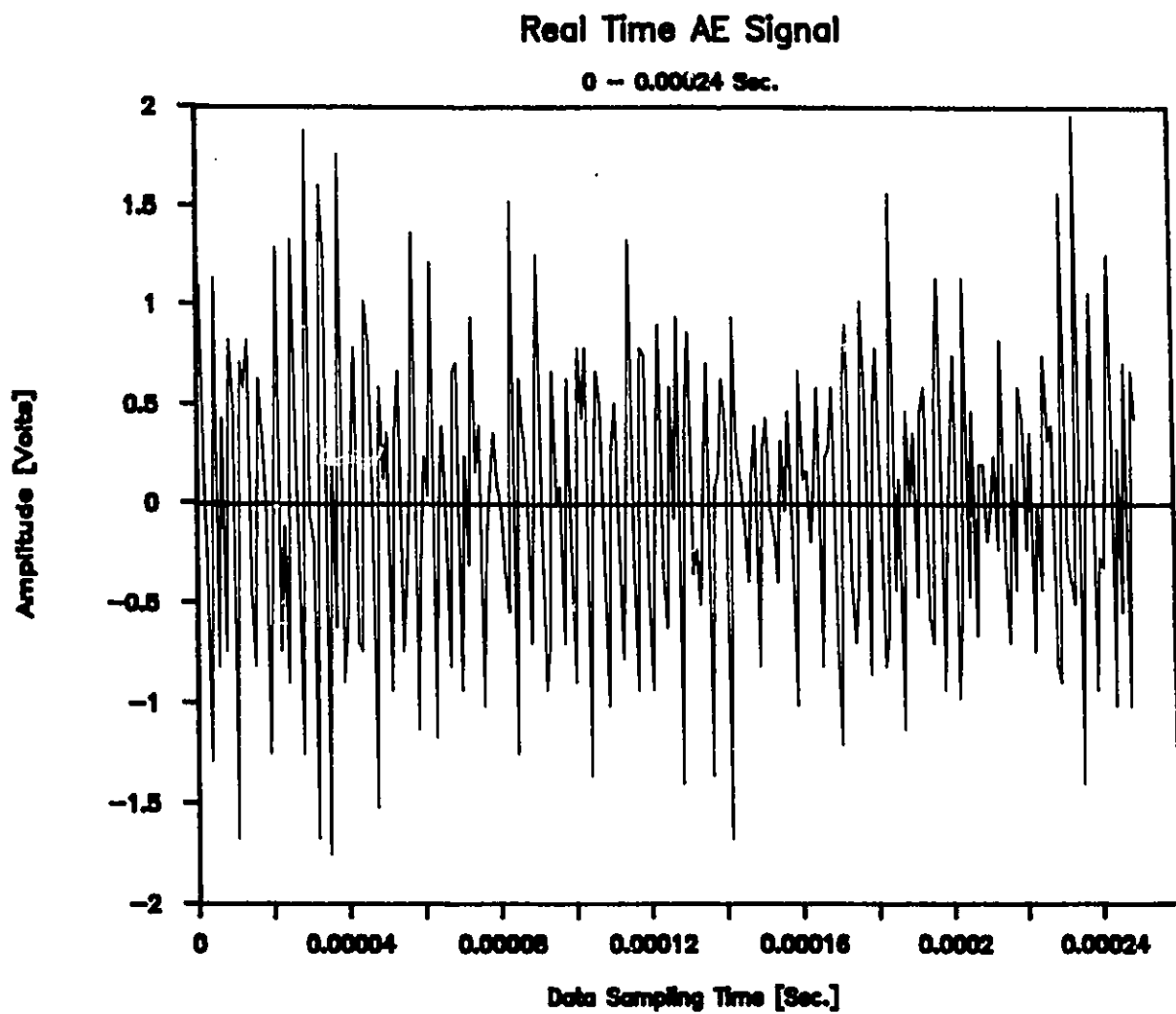


Figure 5.36. Amplitude-time signal from drilling which contains three different characteristics.



5.37. A plot of zoomed signal of Figure 5.36.

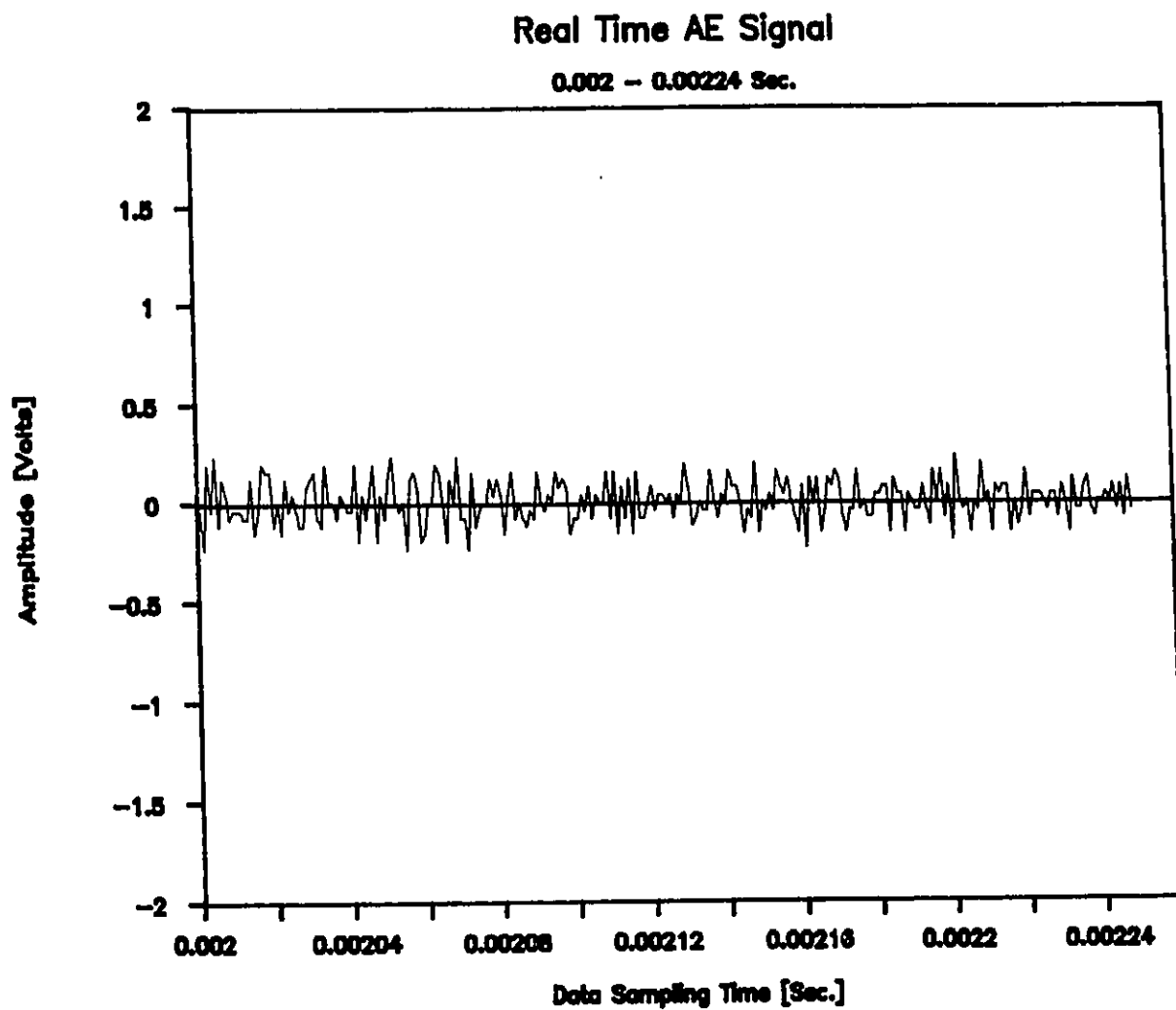


Figure 5.38. A plot of zoomed signal of Figure 5.36.

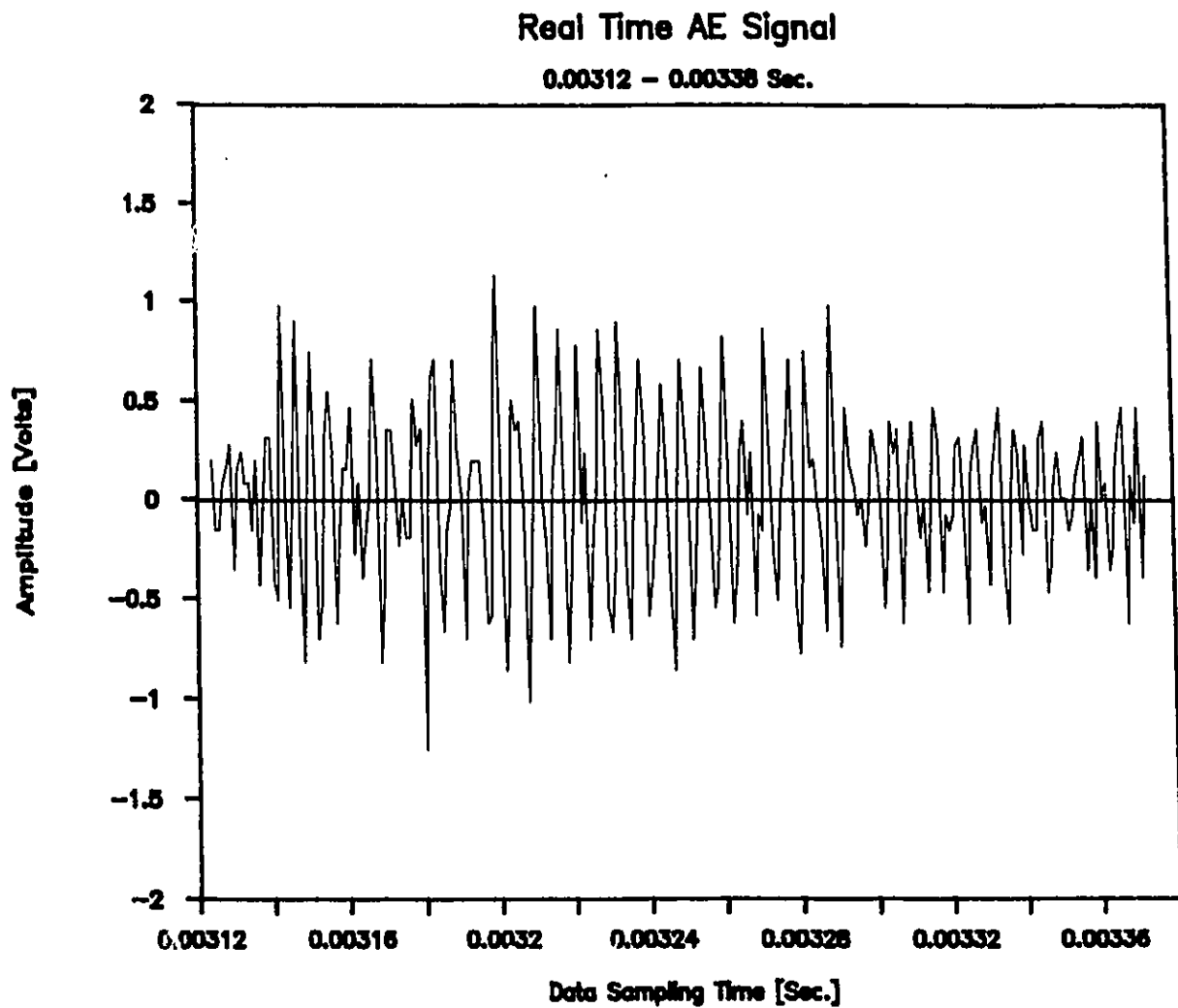


Figure 5.39. A plot of zoomed signal of Figure 5.36.

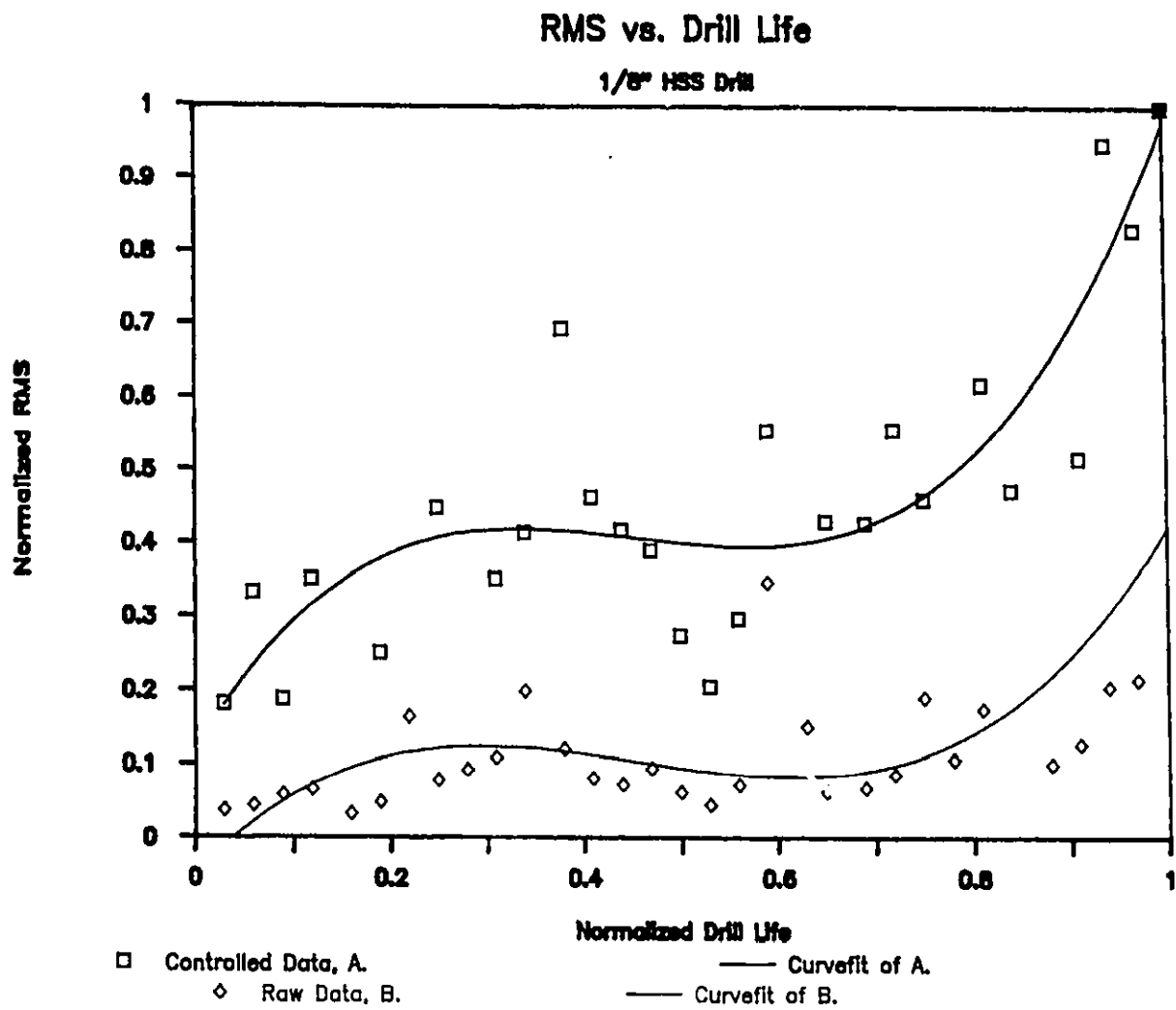


Figure 5.40. Comparison of RMS values which were obtained from controlled data to those of raw data.

5.4.5.4. Mean versus Drill Life

The mean value, which is defined as the sum of all the data values divided by the number of data, the so called arithmetic mean, was calculated for the AE data from initial drilling to observe where the "center" of the data is located. Calculations were repeated until drill failure.

Generally, the mean values of AE signals from drillings are more or less constant for the major portion of the drill life, except at the last few holes, when failure is imminent, significant increases are observed, as shown in Figure 5.41.

5.4.5.5. Skewness and Kurtosis

The skewness, which is defined as the symmetricity of the data about its mean value, was calculated for the AE signals from drilling. A clear property, capable of defining the condition of the drill, was not evident. However, a large scattering of the skewness value was observed for the major portion of drill life, with a noticeable convergence during the last portion when failure was imminent, as shown in Figures 5.42 and 5.43.

The kurtosis, which is a measure of the peakedness of the amplitude distribution, was also calculated from the AE measurements. The corresponding graphs can be seen in Figure 5.44. The values of kurtosis are generally high during normal operation of the drill, but converge to a value of 3 near failure.

This corresponds to a completely random distribution, and a similar trend is observed with normal vibration measurement. However, the repeatability of those results was very poor.

5.4.5.6. Summary of Statistical Results

It is evident that in general the statistical descriptors do not offer useful procedures for the monitoring of the condition of drills. Although relatively low coefficients of correlations were obtained with the data curvefit, RMS and standard deviation versus drill life show some repeatable results. Similarly, the significant increases of the mean value close to drill failure were repeatable and may be useful for short term predictions. An examination of the usefulness of kurtosis and skewness indicates inadequate repeatability for practical applications.

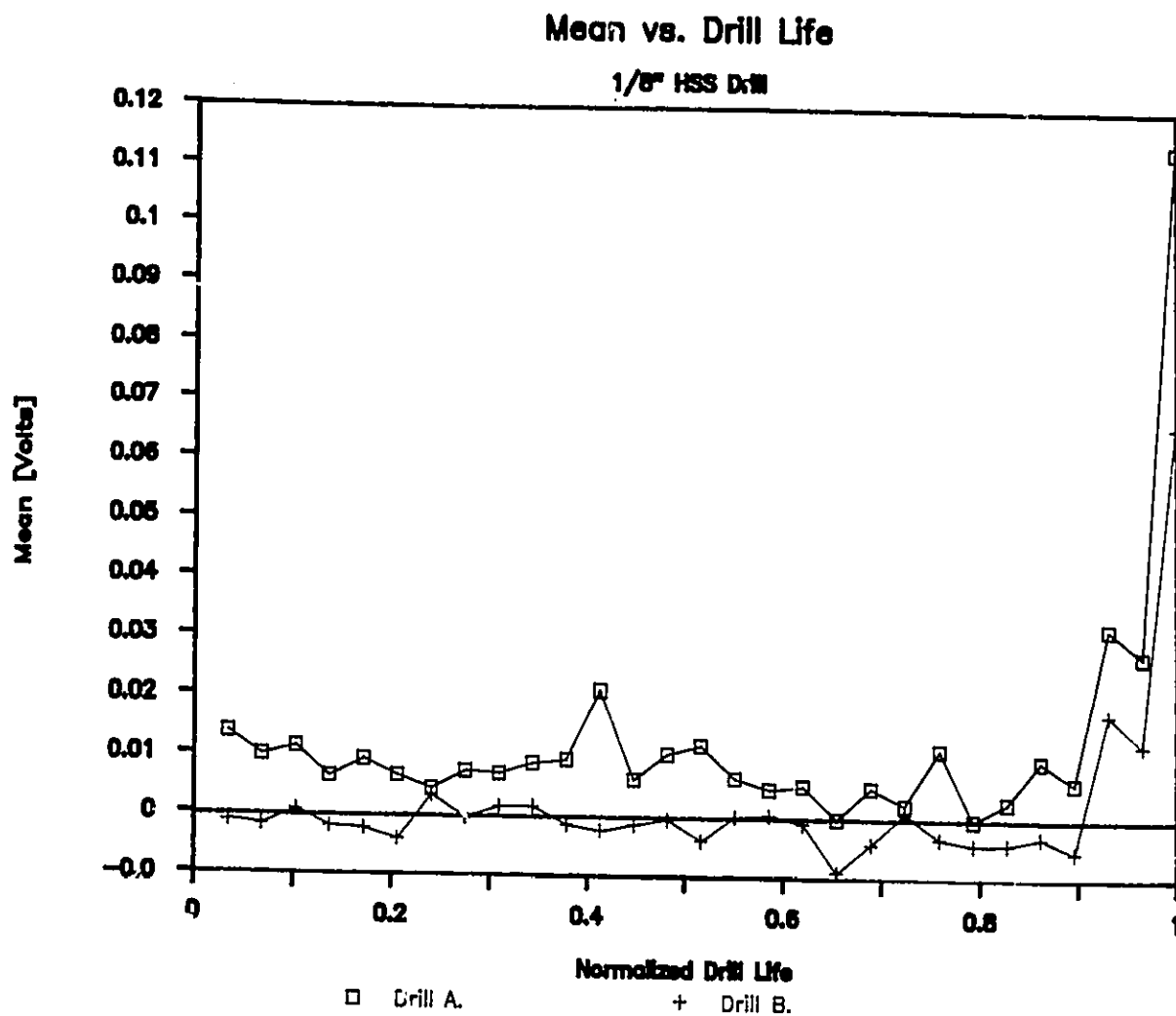


Figure 5.41. Plot of mean versus drill life.

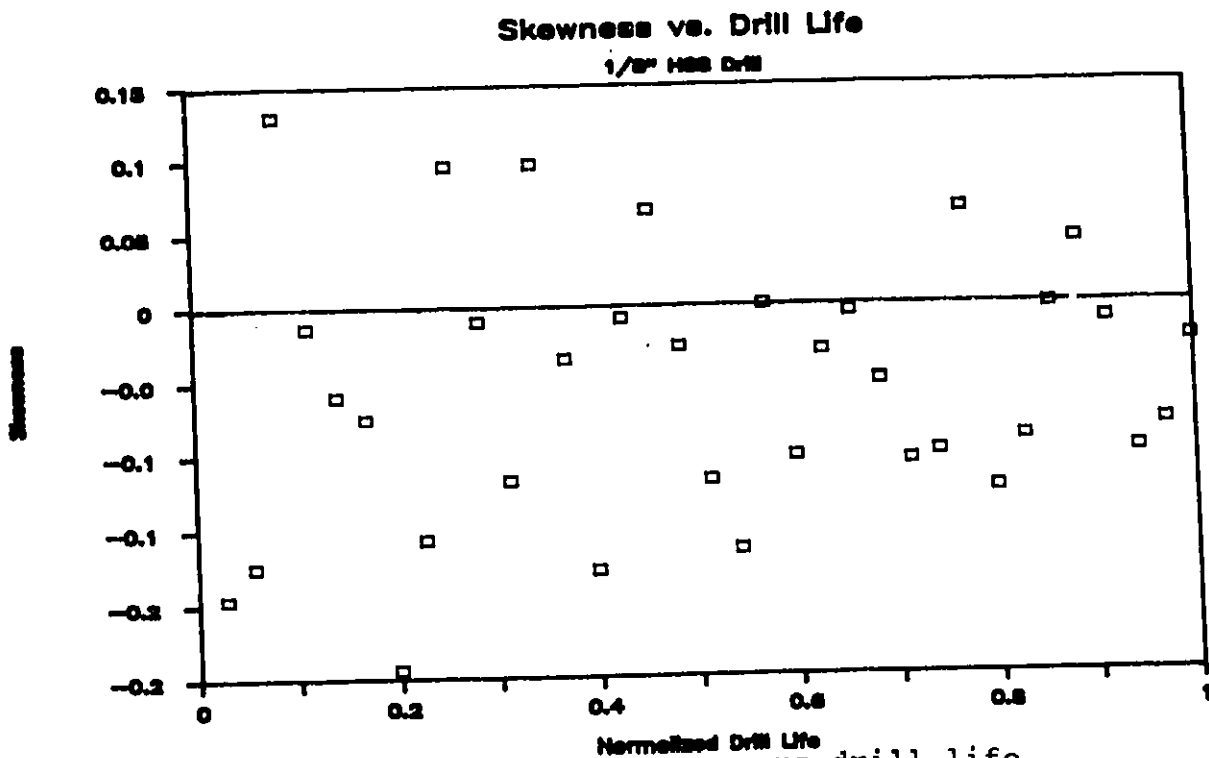


Figure 5.42. plot of skewness versus drill life.

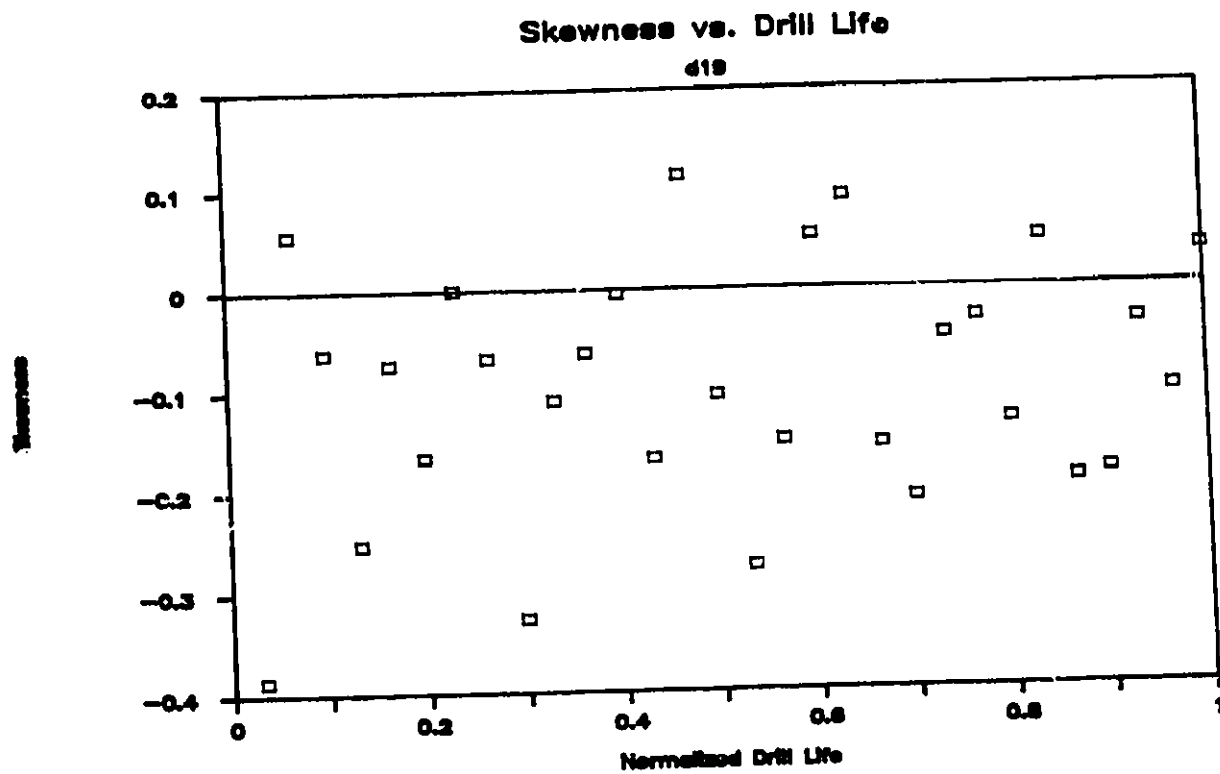


Figure 5.43. Plot of skewness versus drill life.

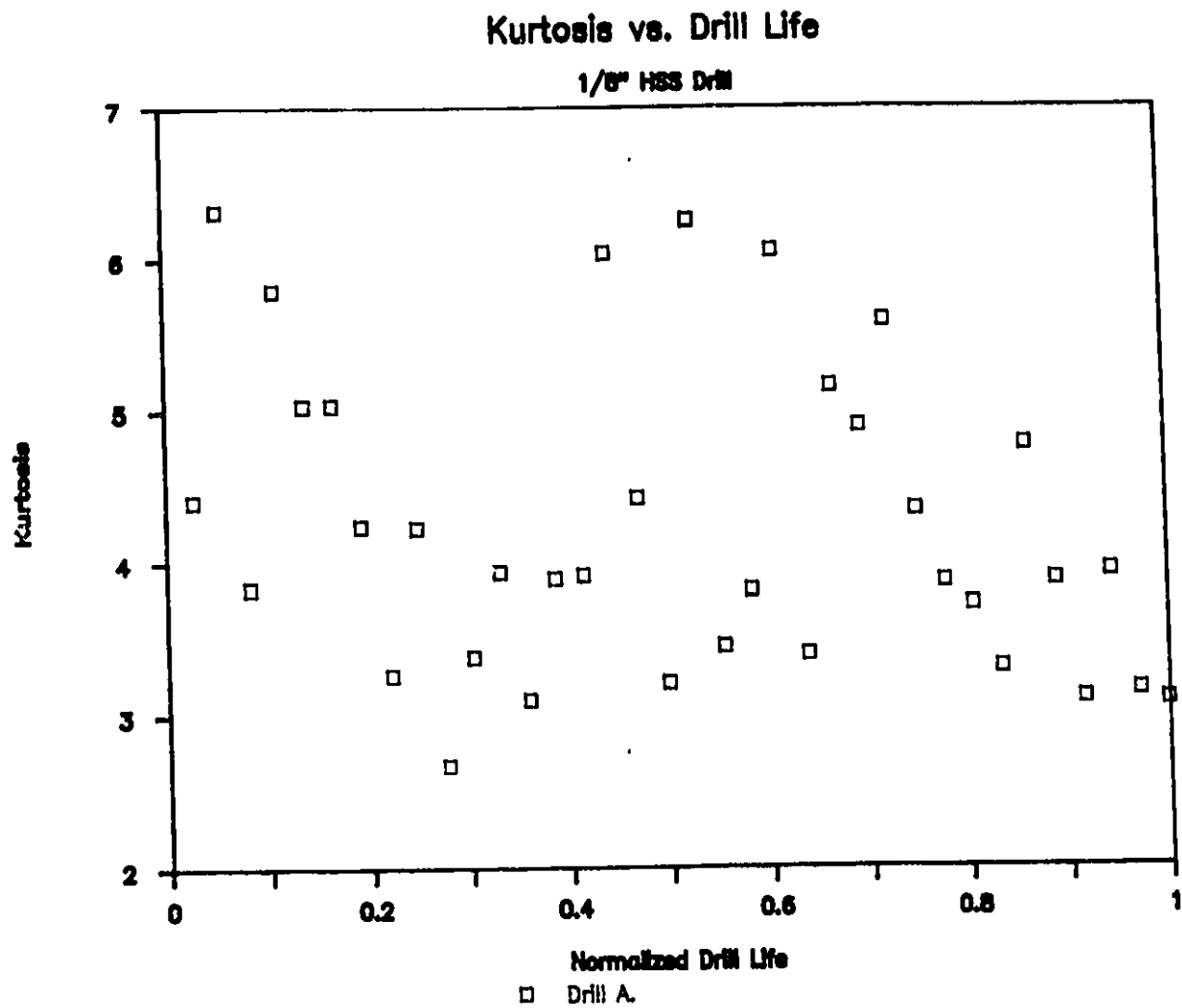


Figure 5.44. Plot of kurtosis versus drill life.

5.4.6. Frequency Domain Signal Analysis

The time domain analysis of the AE signal resulted in some useful parameters that relate reasonably well to the drill situation. In all results the irregular variation of the signal during each cut was studied and was obviously the main reason for the inconsistencies observed. In order to reduce this effect it was decided to analyze the results in segments of each cut and combine and evaluate those of similar behavior.

5.4.6.1. Power Spectra of AE Signals

In this study, predominant frequency range implies the frequency range that is most promising in relating drill wear or drill breakage to the analyzed AE results. It was assumed that the power spectra in different frequency ranges represent the different sources of AE generation, which are mechanical noise, strain energy from cutting and other actions from drilling. At first, frequency spectrum of AE data from different events were observed.

Mechanical noise, which was generated by impacting the tool post with a hammer, was captured by digital oscilloscope, and samples of 16K points of digitized AE data were analyzed. The power spectra of mechanical noise were observed in the frequency range of 110 to 180 kHz and a peak amplitude appeared at 135 kHz as shown in Figure 5.45. It was compared to the power spectra of

AE signals, which were obtained from drilling with a center drill and with a sharp drill, as shown in Figures 5.46 and 5.47 respectively. From it, several distinct and predominant peaks were evident. Only one of them at 135 kHz corresponded to the result obtained in the mechanical noise test. In Figures 5.48, 5.49 and 5.50, the power spectra from the analysis of drilling data with worn drills are shown. The predominant peaks were compared to those obtained with a sharp drill, Figure 5.47. Several distinct peaks were observed, particularly at 407 kHz which were only present with low amplitude in the latter Figure. The peaks at 110 kHz correspond to mechanical noise.

In an attempt to relate the magnitude of the time domain signal amplitude to the frequency characteristics, frequency analyses of selected amplitude groups, were carried out. The signal depicted in Figure 5.51 represents one set of the AE signal which corresponds to 0.016 seconds of drilling duration. The signal contains several groups of different amplitude levels. Frequency analysis was performed for the five groups of different amplitude levels and corresponding power spectra for the different groups of raw data are shown in Figures 5.52 to 5.57. From the relatively steady and low amplitude data of groups I and III, the power spectra show low amplitudes and no distinct peaks, as shown in Figures 5.53 and 5.55 respectively. Figure 5.54 shows the spectrum for group II, which contains an amplitude burst. A peak at 380 kHz is evident. The spectrum for the burst type signal from data group IV is shown in Figure 5.56 with dominant peaks in

the frequency range 110 to 150 kHz. For the large amplitude data of group V, the spectrum in Figure 5.57, exhibits several peaks which are distributed over all the frequency range. Comparison of the spectrum of each group of data to the spectrum of entire data(16K data points) indicates an almost complete domination by components from the signal in group V, as shown in Figure 5.52. As a result of this analysis, it is obvious that the AE signal from drilling will generally contain many different events and a set of data of 0.016 seconds duration is very unlikely to produce consistent results. A less precise averaging method over the period of the cut is likely to produce better results.

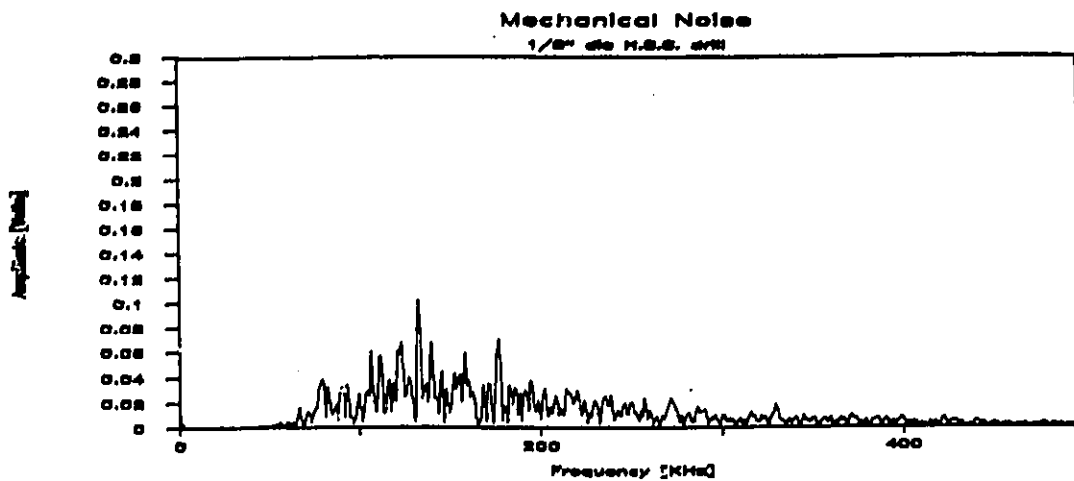


Figure 5.45. Frequency spectrum of mechanical noise.

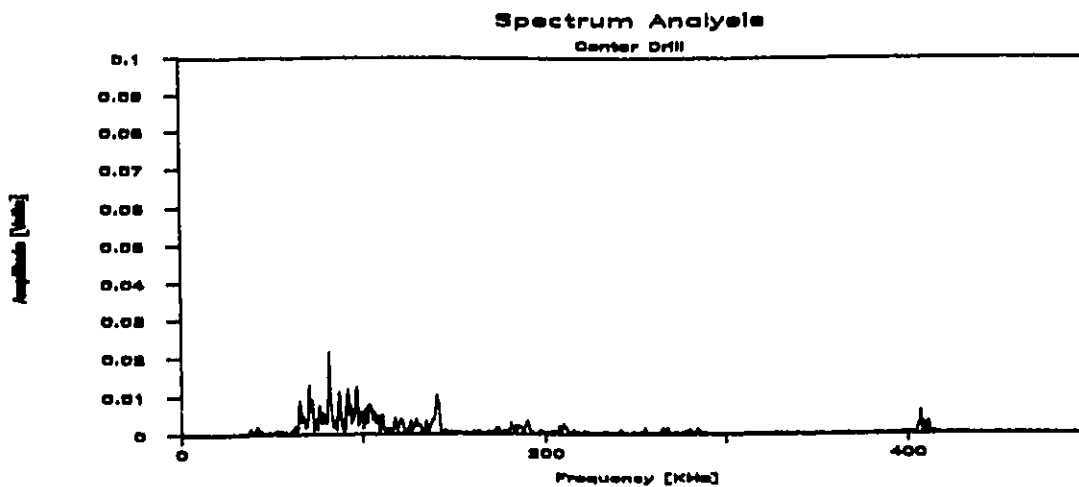


Figure 5.46. Frequency spectrum of AE signal from center drill.

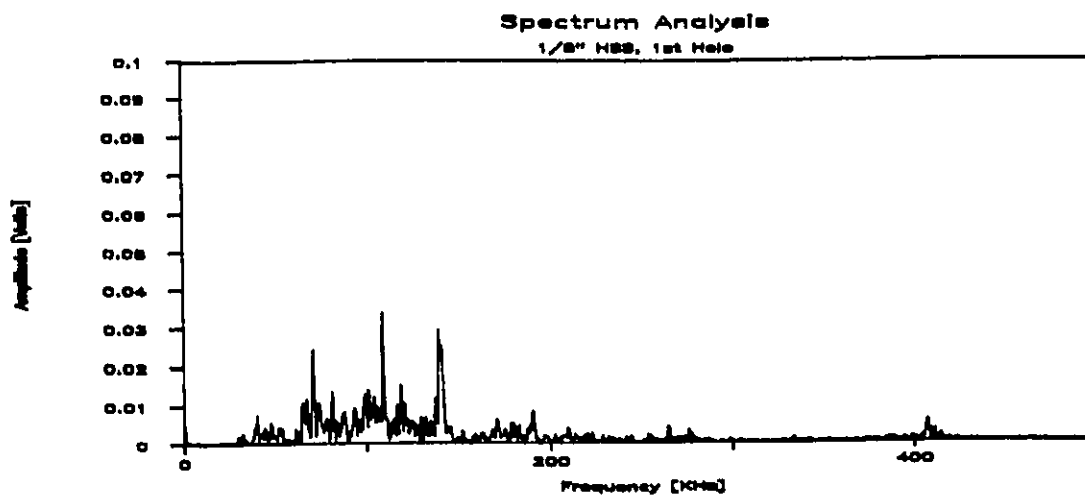


Figure 5.47. Frequency spectrum of AE signal from drilling with a sharp drill.

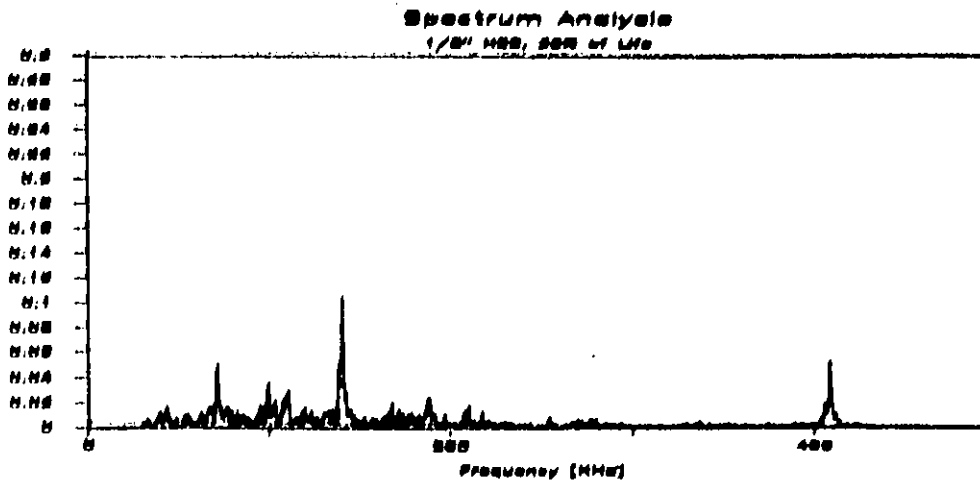


Figure 5.48. Frequency spectrum of AE signal from drilling - at 35 % of drill life.

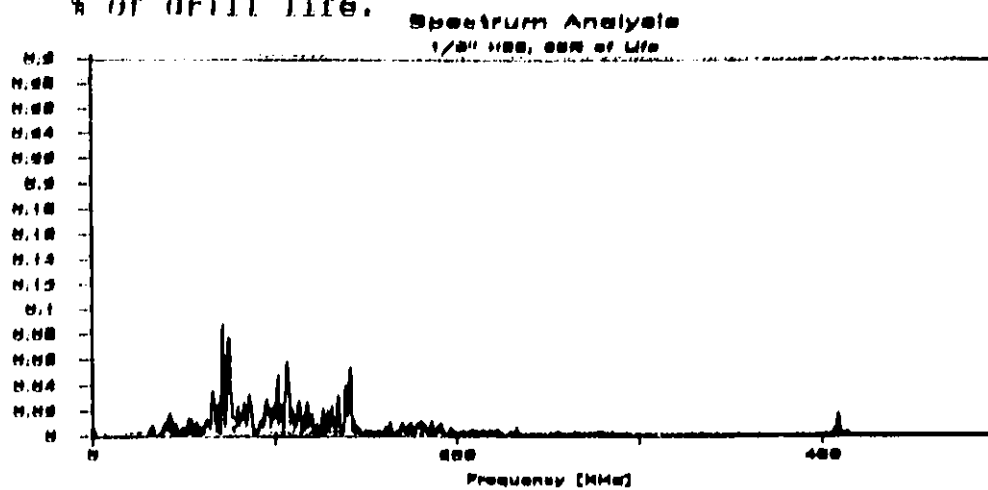


Figure 5.49. Frequency spectrum of AE signal from drilling - at 60 % of drill life

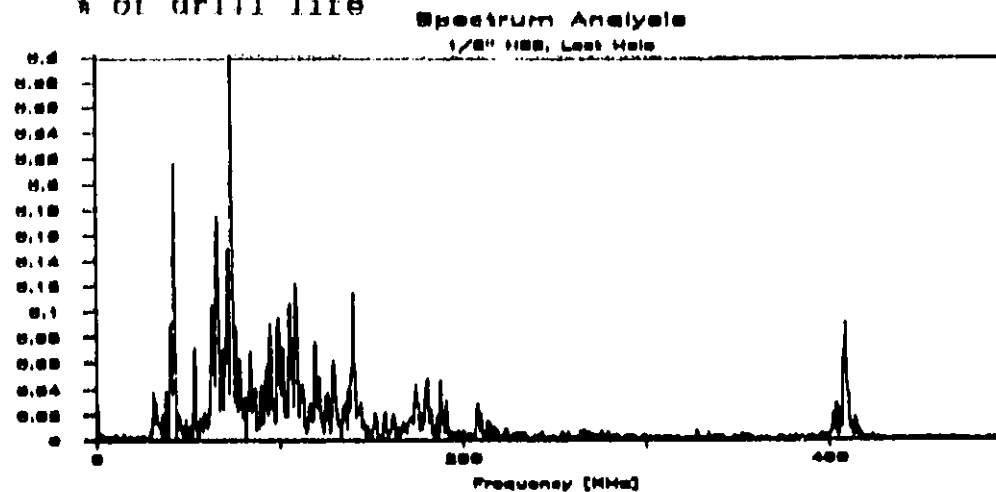
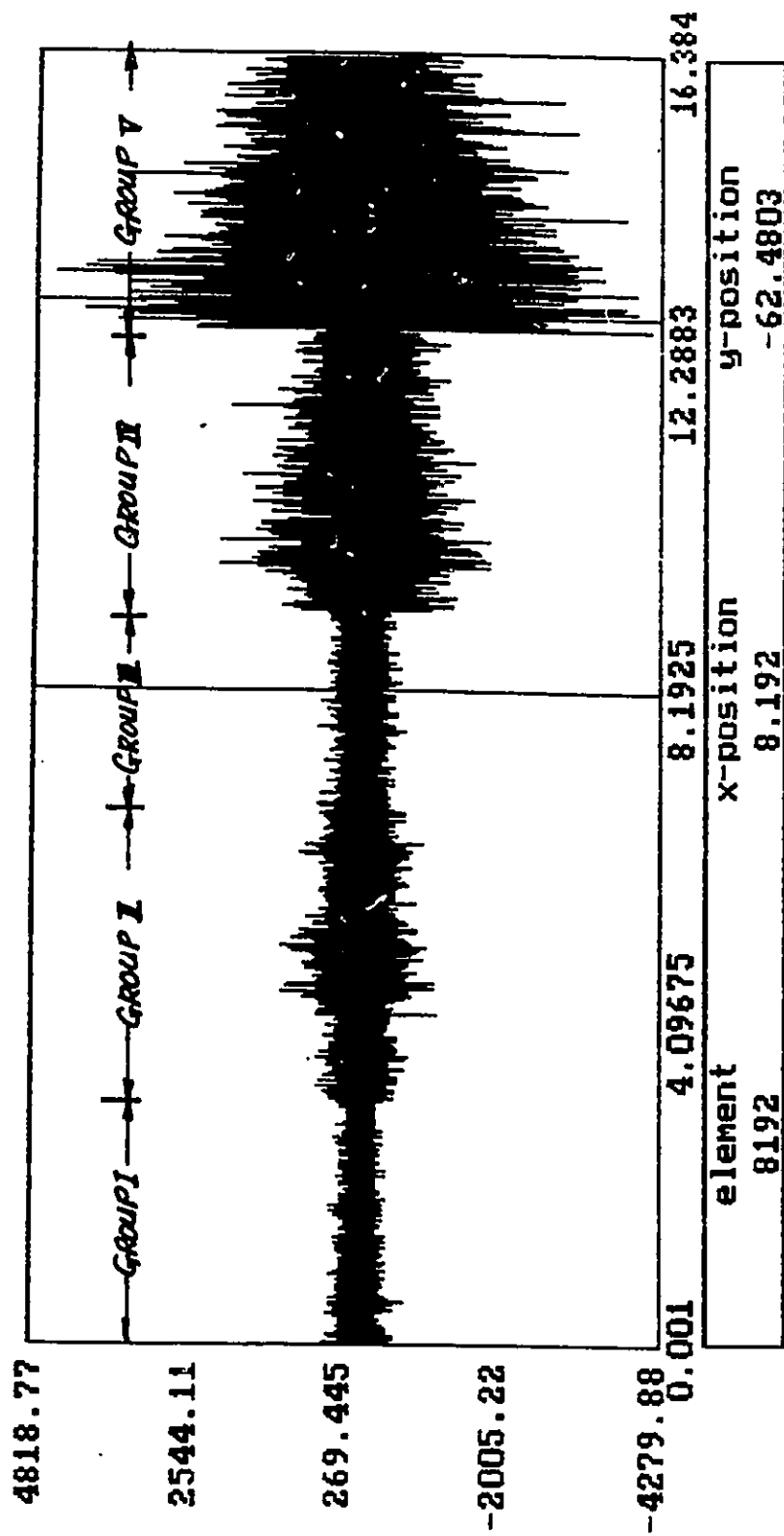


Figure 5.50. Frequency spectrum of AE signal from drilling - when failure was imminent.



press:
 -cursor keys to move -I to zoom in
 -(1-6) to change speed -0 to zoom out
 -Q to quit

Figure 5.51. A characteristics of AE signal which contains five different amplitude groups.

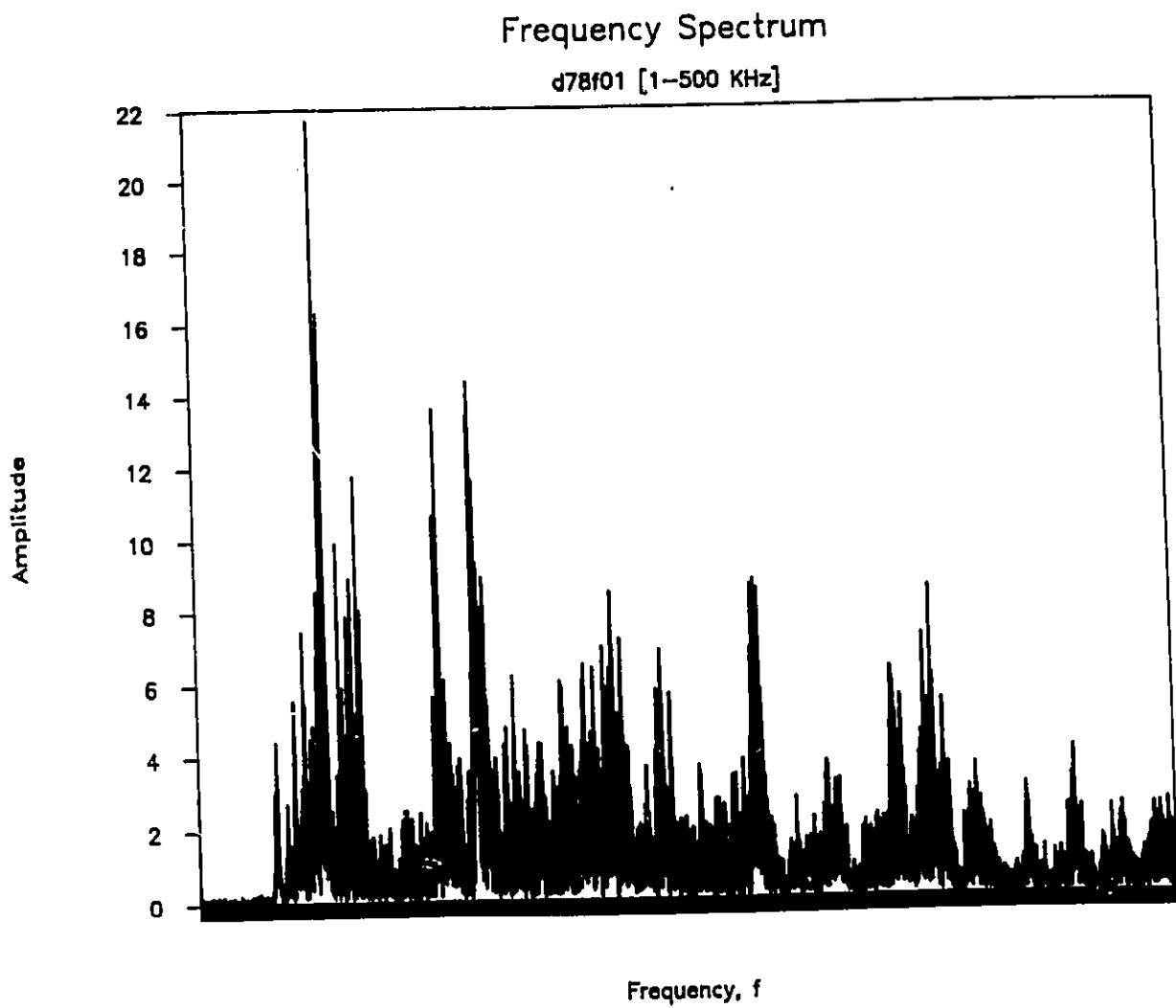


Figure 5.52. Frequency spectrum of the 16k points of AE signal from drilling.

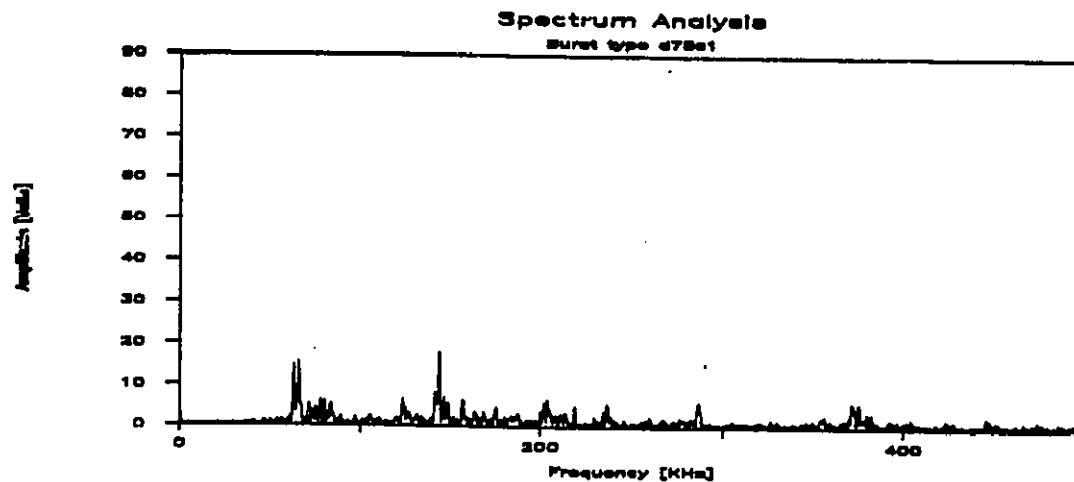


Figure 5.53. Frequency spectrum of AE signal - Group I.

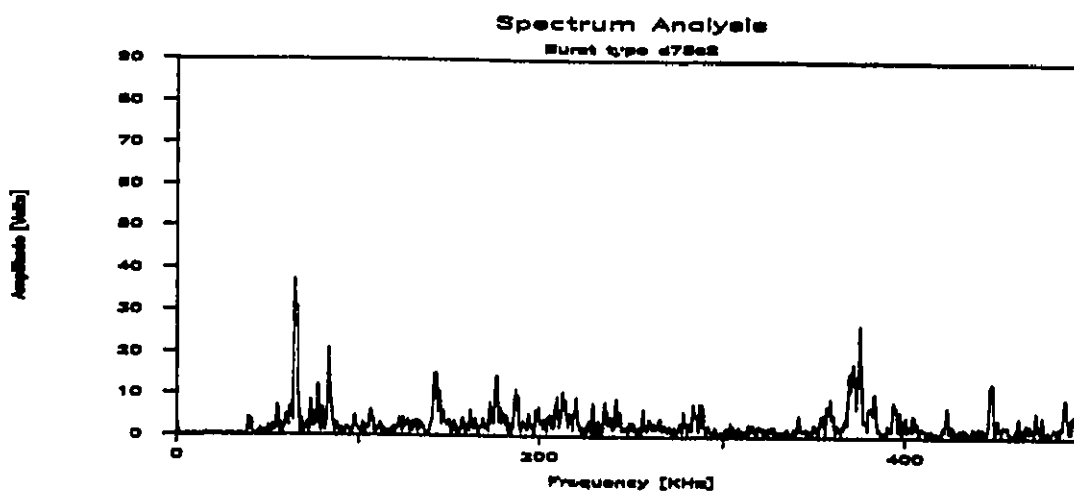


Figure 5.54. Frequency spectrum of AE signal - Group II

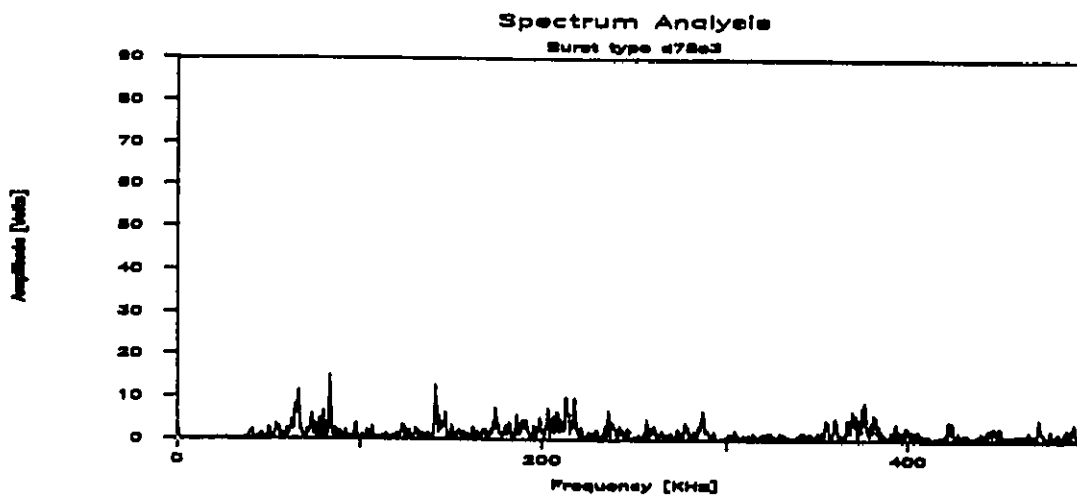


Figure 5.55. Frequency spectrum of AE signal - Group III.

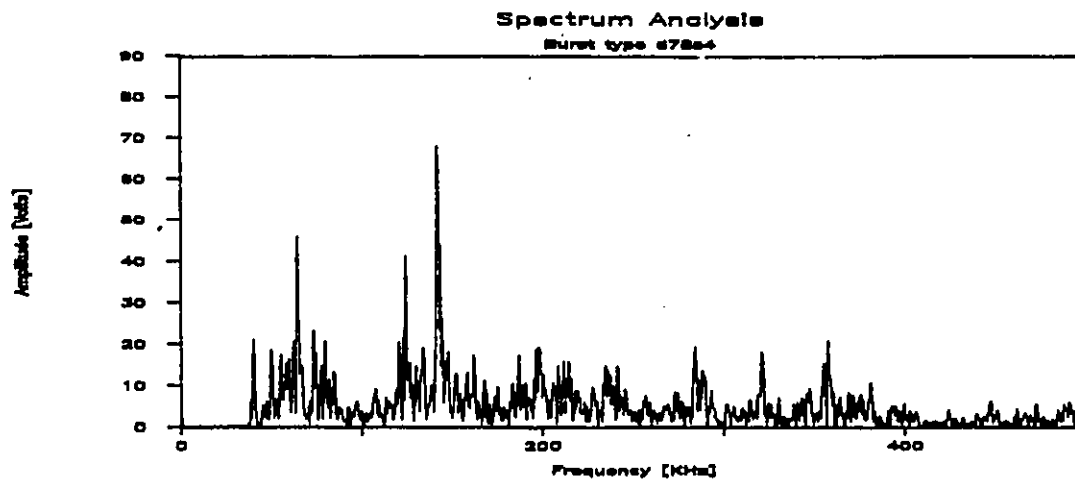


Figure 5.56. Frequency spectrum of AE signal - Group IV.

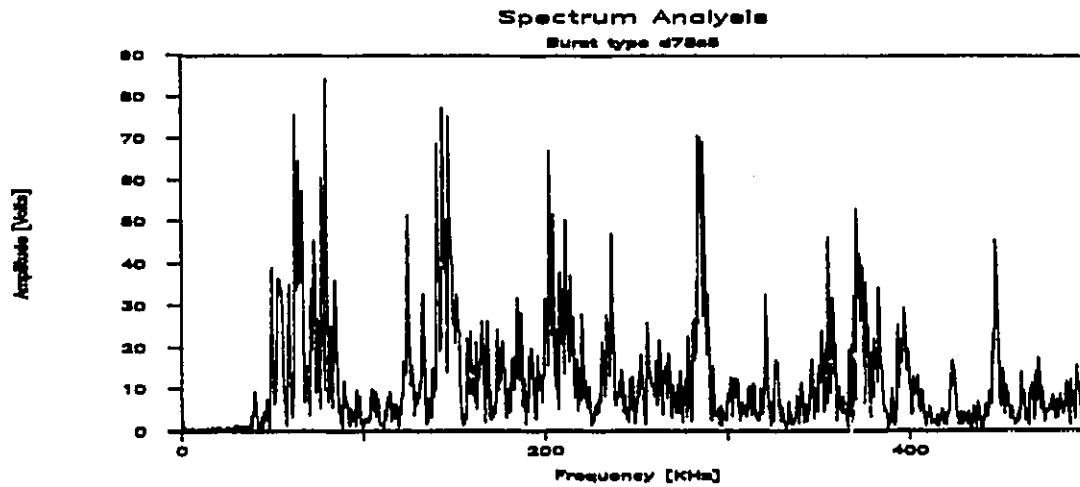


Figure 5.57. Frequency spectrum of AE signal - Group V.

5.4.6.2. Lower Frequency Range FFT Analysis - 50 to 102 kHz

The analysis of results in the full frequency range had the instrumentation imposed disadvantage of short duration digitized sample, together with the unsteady type of signal. This is partly overcome by the use of the commercial analyzer HP 4320 with a frequency range of up to 102.4 kHz. The measurements cover the longer drilling period and thus offer better results, but at a lower frequency range. The spectra of initial drilling and that of drill failure are shown in Figures 5.58, 5.59 and 5.60, and the amplitudes at 66.6 and 80 kHz versus normalized drill life are plotted in Figure 5.61. Discrete components at approximately 67 kHz, with varying magnitude, appear in all spectra. Only near failure, another and much larger component is present at 80 kHz. Although these results are reasonably good their potential for monitoring purposes is not very good due to lack of repeatability.

5.4.6.3. Narrow Band Spectrum Analysis

It was observed that, generally, the power spectra from sharp drills were of low amplitude and reasonably uniform, but as the drills became progressively more dull, distinct peaks appeared at different frequencies. To investigate this condition more closely, narrow band spectrum analysis was performed on AE data.

The procedures of narrow band analyses are expressed by the well known power spectral density equation as follows:

$$BWA_{i,j} = \sum_{f=i}^j Sx(f) \quad (39)$$

where the BWA is the summation of amplitudes in the selected bandwidth with the frequency range from i to j, and $Sx(f)$ is the amplitude at the frequency f. The bandwidth frequency range, i and j, were selected at the beginning and ending of distinct peaks respectively.

As shown in Figure 5.52, nineteen groups of peaks were observed in different frequency ranges from one hole drilling. The summed amplitudes of those 19 bandwidths are compared to find the most related bandwidth with drilling and the differences in trends are plotted against the normalized drill life, as shown in Figures 5.62 to 5.65. Normalized summed amplitudes, which are defined as the summed RMS amplitudes for a given set of data divided by the corresponding value at drill failure, are used so that comparisons with different bandwidth and drills can be made. It was repeated for the sets of drilling data and the best results are produced in the frequency range of 100 - 150 kHz. The Figures 5.66 to 5.69. show the summed amplitude in the frequency range of 100 kHz to 150 kHz versus normalized drill life for different drills. The correlations between amplitude change and drill life were shown also with the use of third degree polynomial curvefit program and a similar trend to that obtained with AE count versus drill life was observed, although the correlation coefficients of

the curvefits are lower than those of AE count. It is perhaps worth mentioning at this point that similar trends in the same AE frequency band have been found in the case of rolling element bearing failures. However, some of the results indicate very rapid increase of the band amplitude only near the drill failure, as shown in the Figures 5.70 and 5.71. For these particular results, logarithmic values of summed amplitudes versus normalized drill life were plotted, as shown in Figures 5.72 and 73. A similar trend with that of normal results, which are shown in Figures 5.66 to 5.69, is observed.

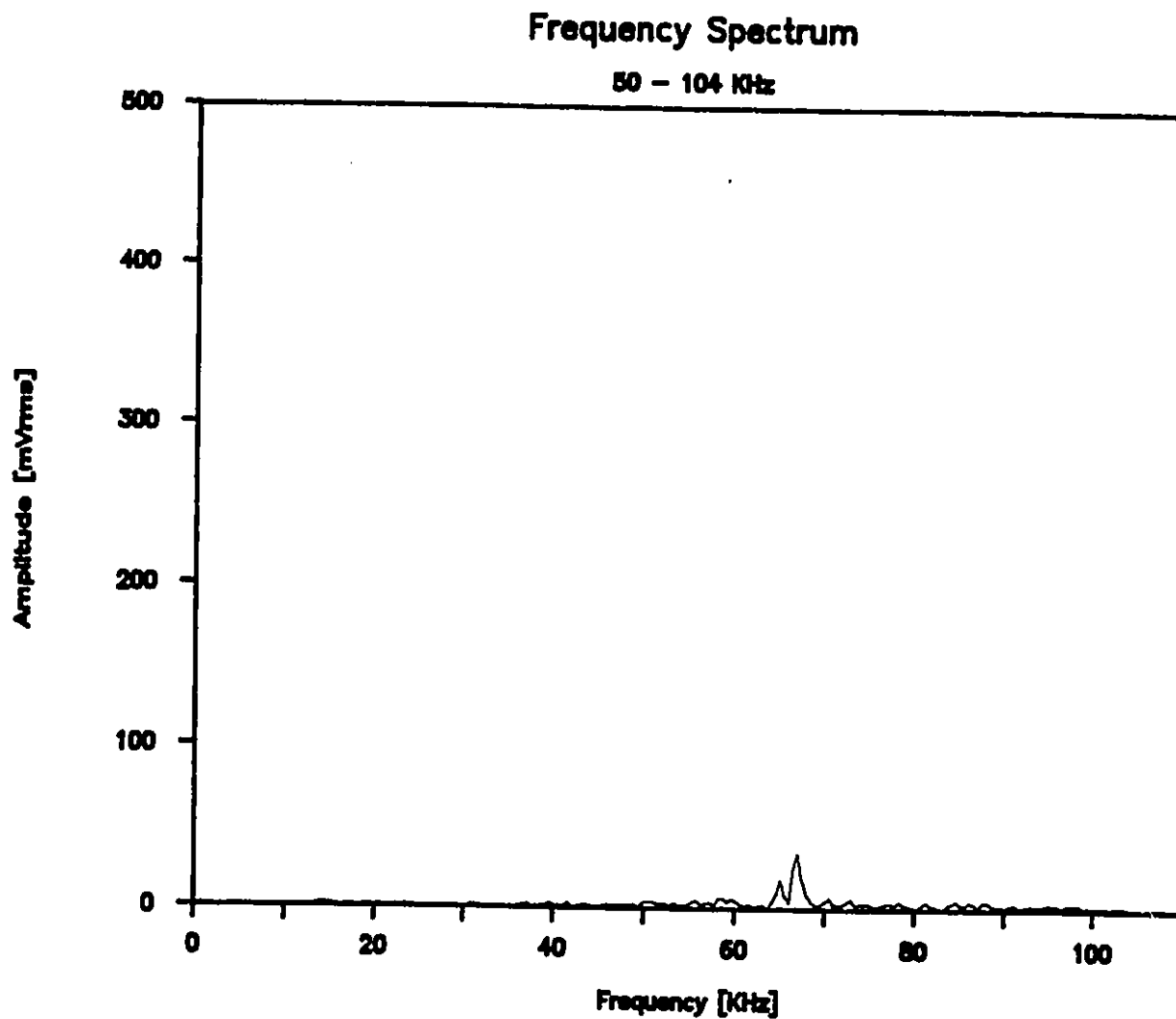


Figure 5.58. Lower range frequency spectrum of AE signal - with a sharp drill.

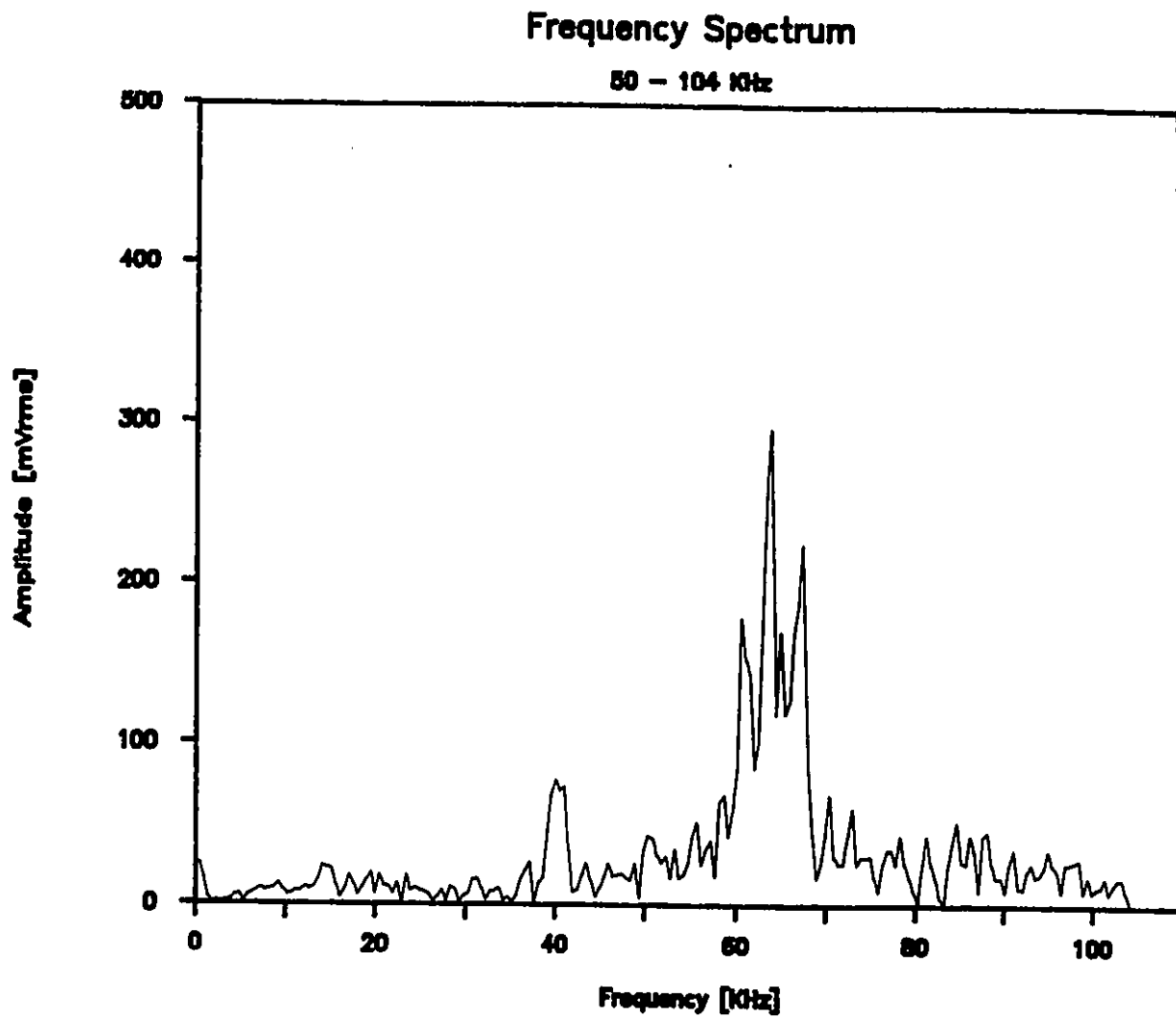


Figure 5.59. Lower range frequency spectrum of AE signal - at 50 percent of drill life.

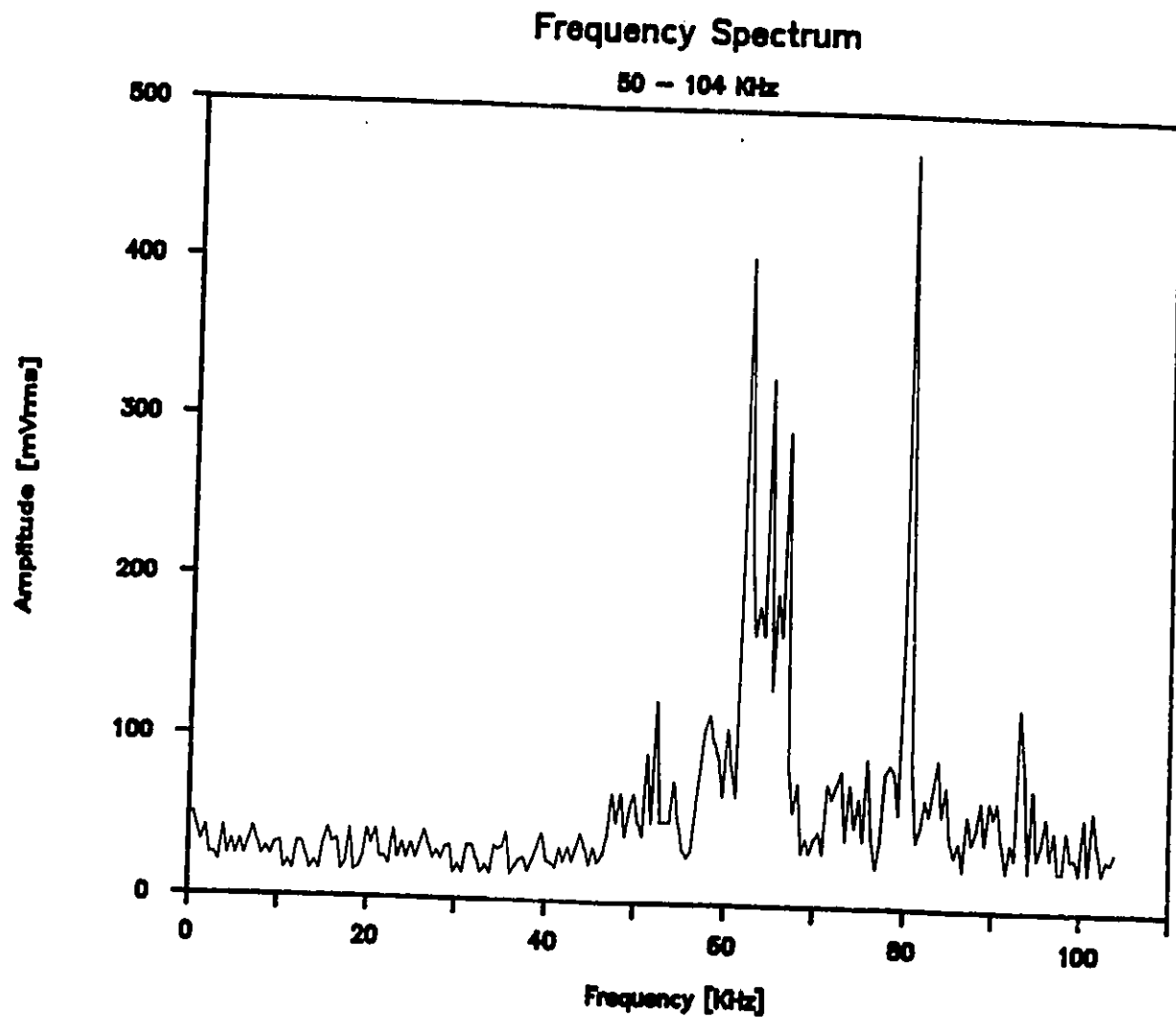


Figure 5.60. Lower range frequency spectrum of AE signal - when failure was imminent.

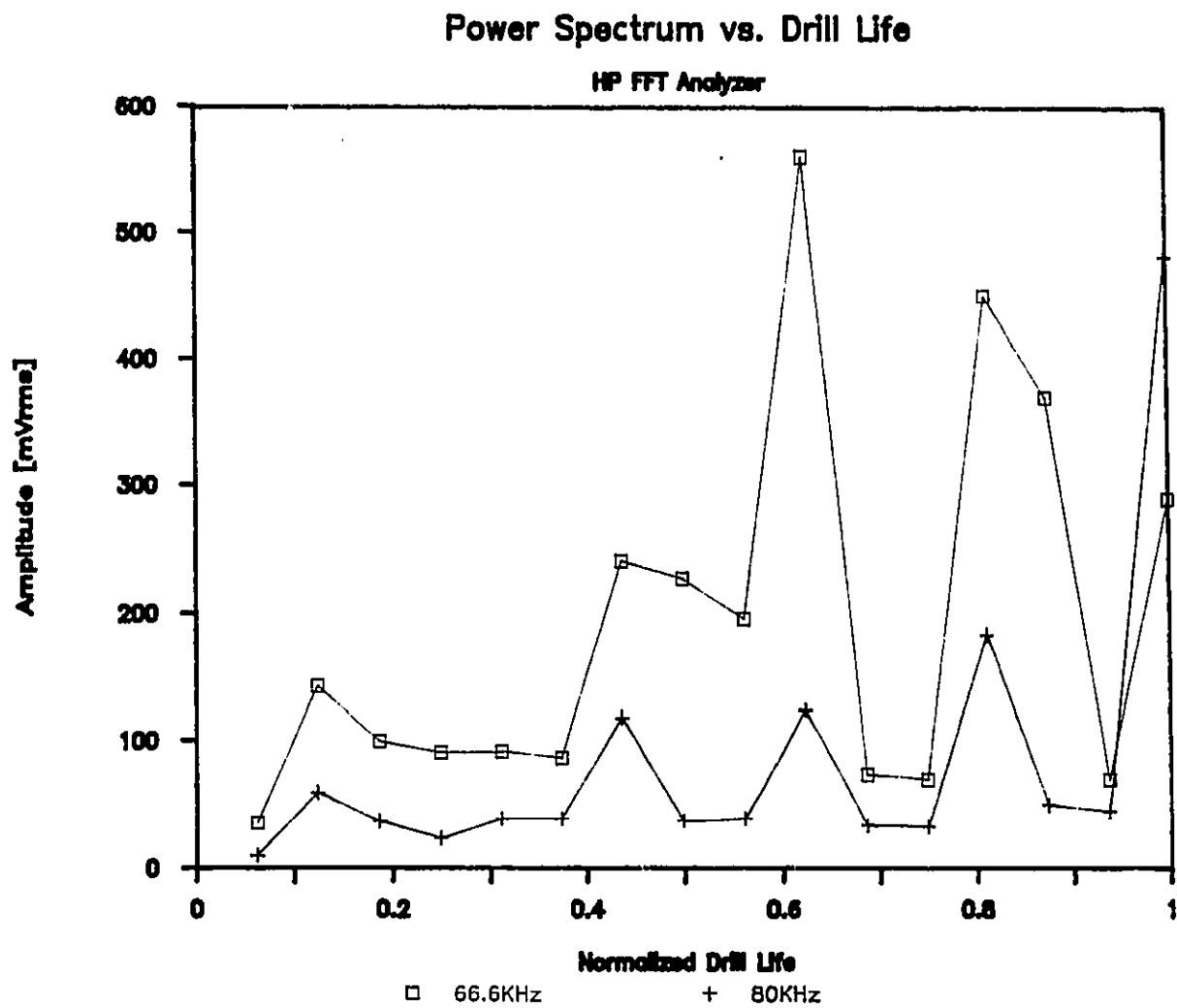


Figure 5.61. Lower frequency power spectrum versus drill life.

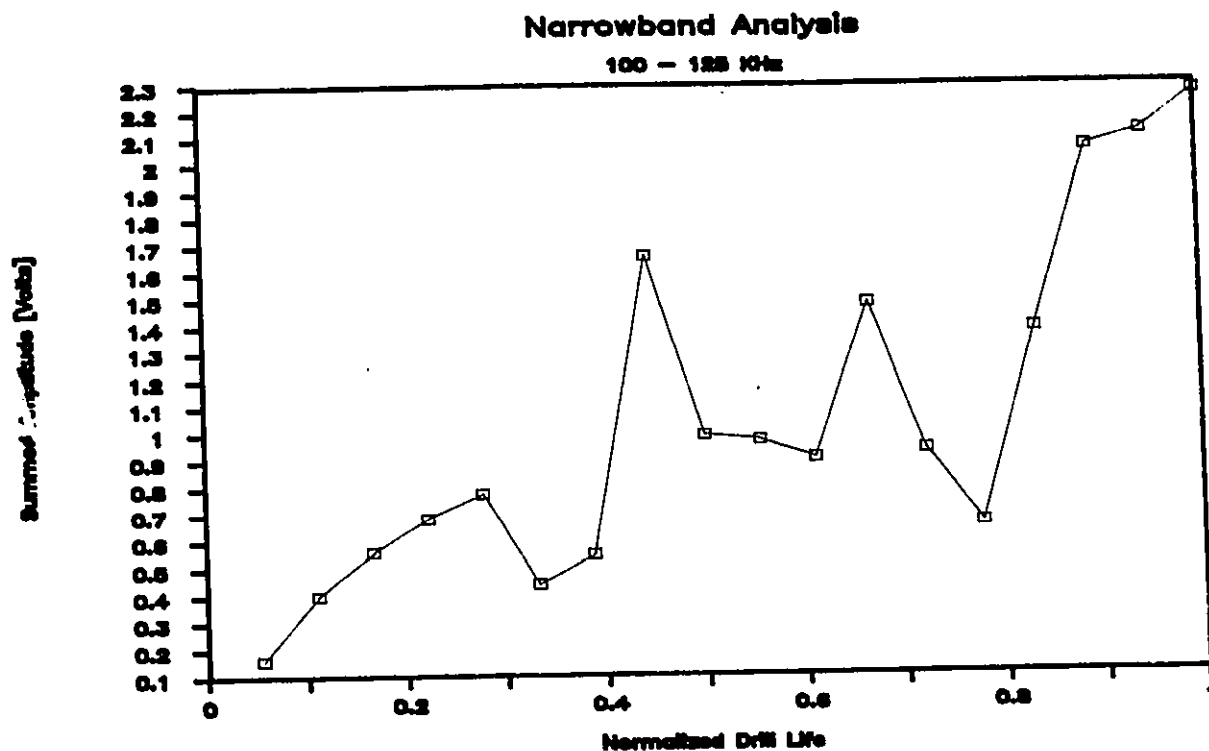


Figure 5.62. Summed amplitude versus drill life - bandwidth 100 - 125 kHz.

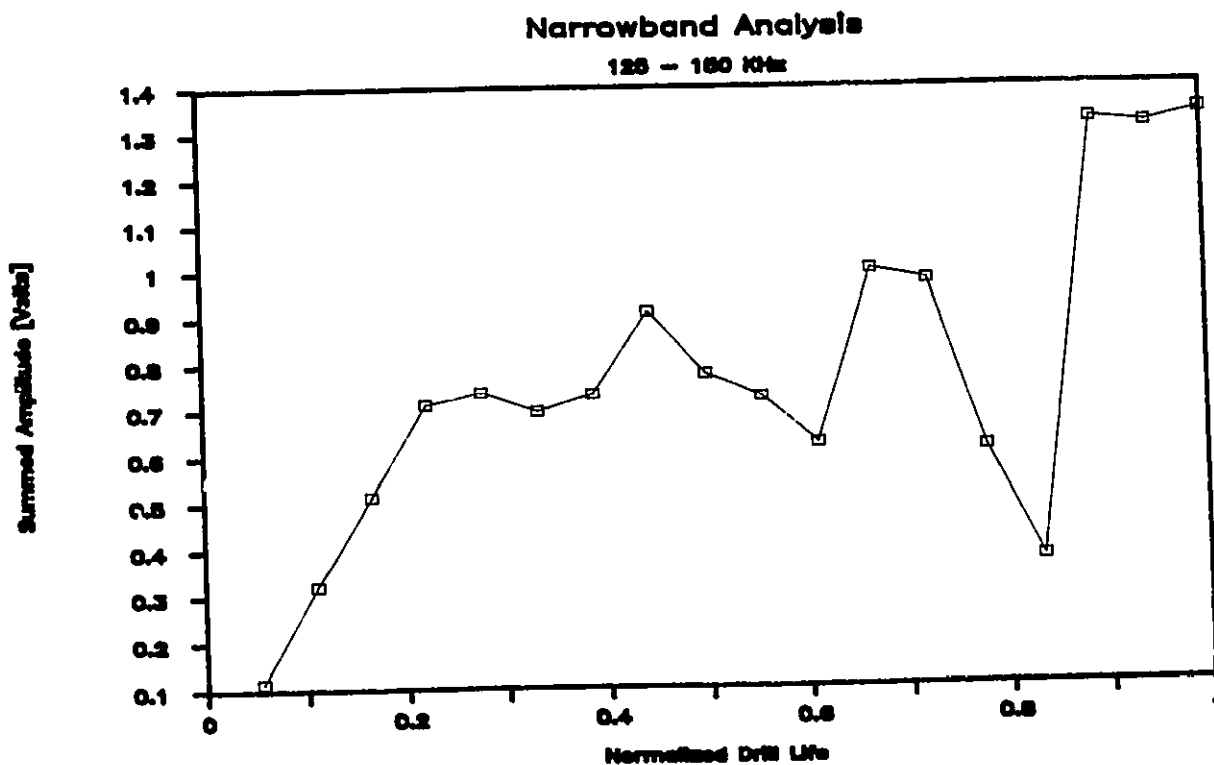


Figure 5.63. Summed amplitude versus drill life - bandwidth 125 - 150 kHz.

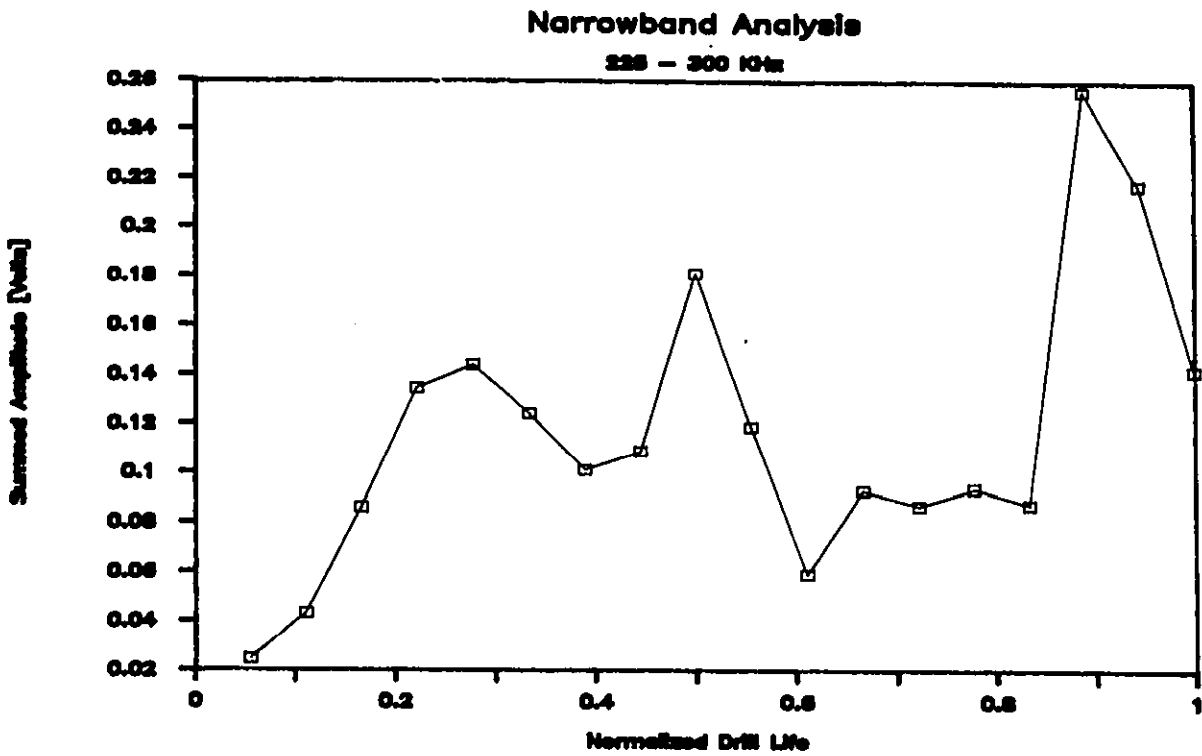


Figure 5.64. Summed amplitude versus drill life - bandwidth 225 - 300 KHz.

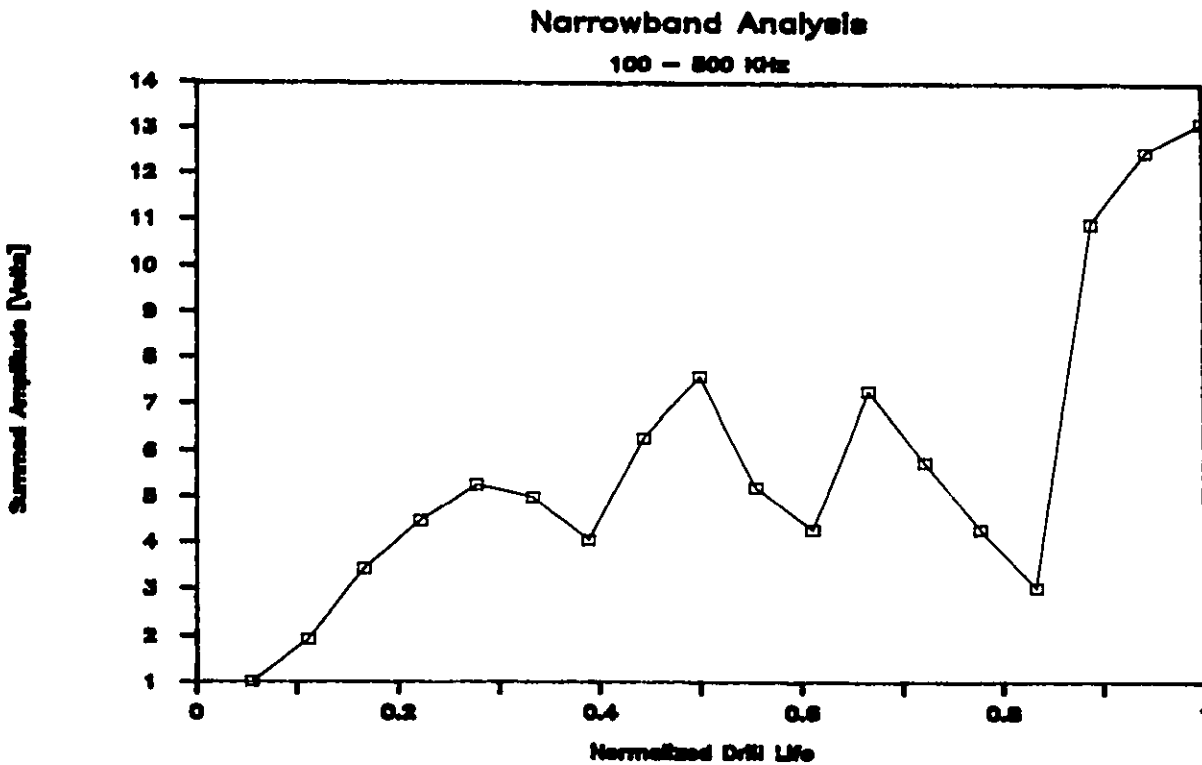


Figure 5.65. Summed amplitude versus drill life - bandwidth 100 - 500 KHz.

Narrow Band Analysis

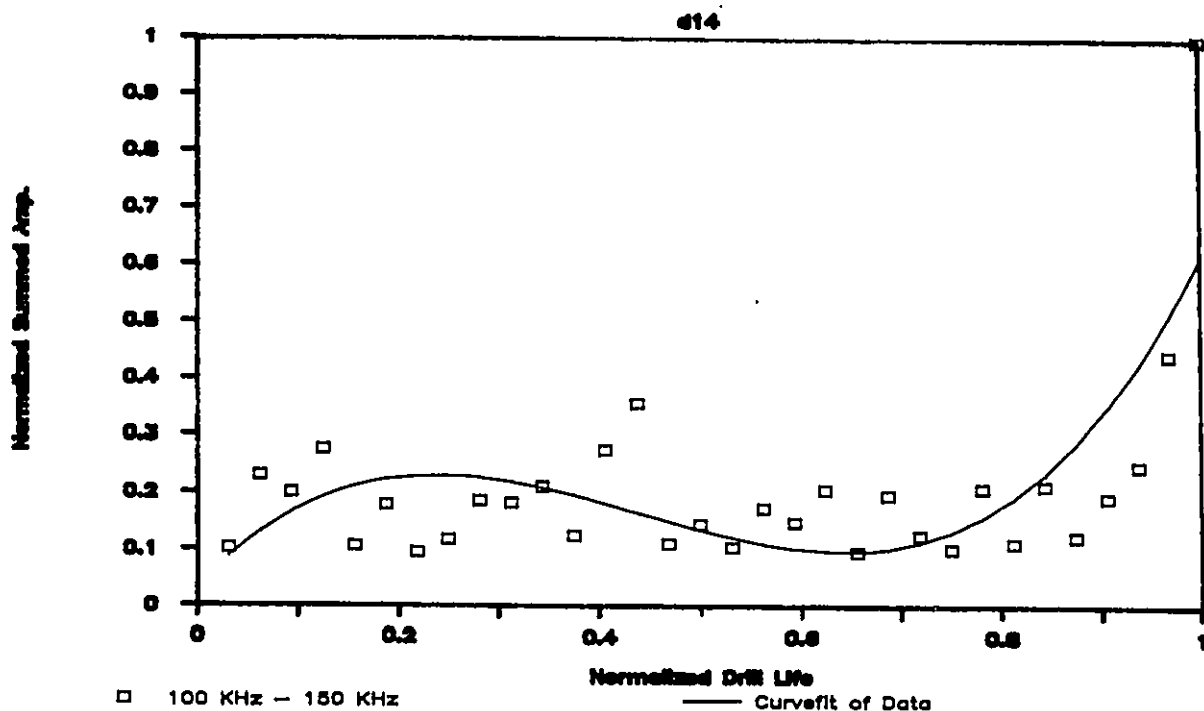


Figure 5.66. Summed amplitude versus drill life - bandwidth 100 - 150 KHz.

Narrow Band Analysis

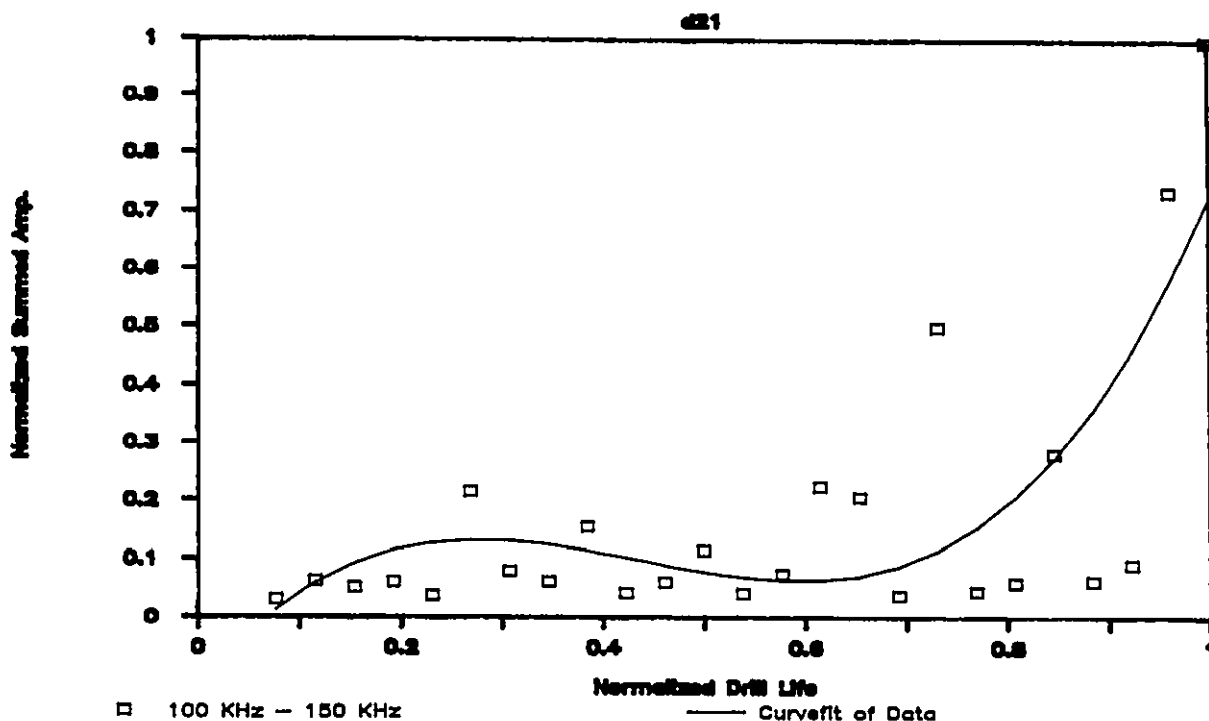


Figure 5.67. Summed amplitude versus drill life - bandwidth 100 - 150 KHz.

Narrowband Analysis

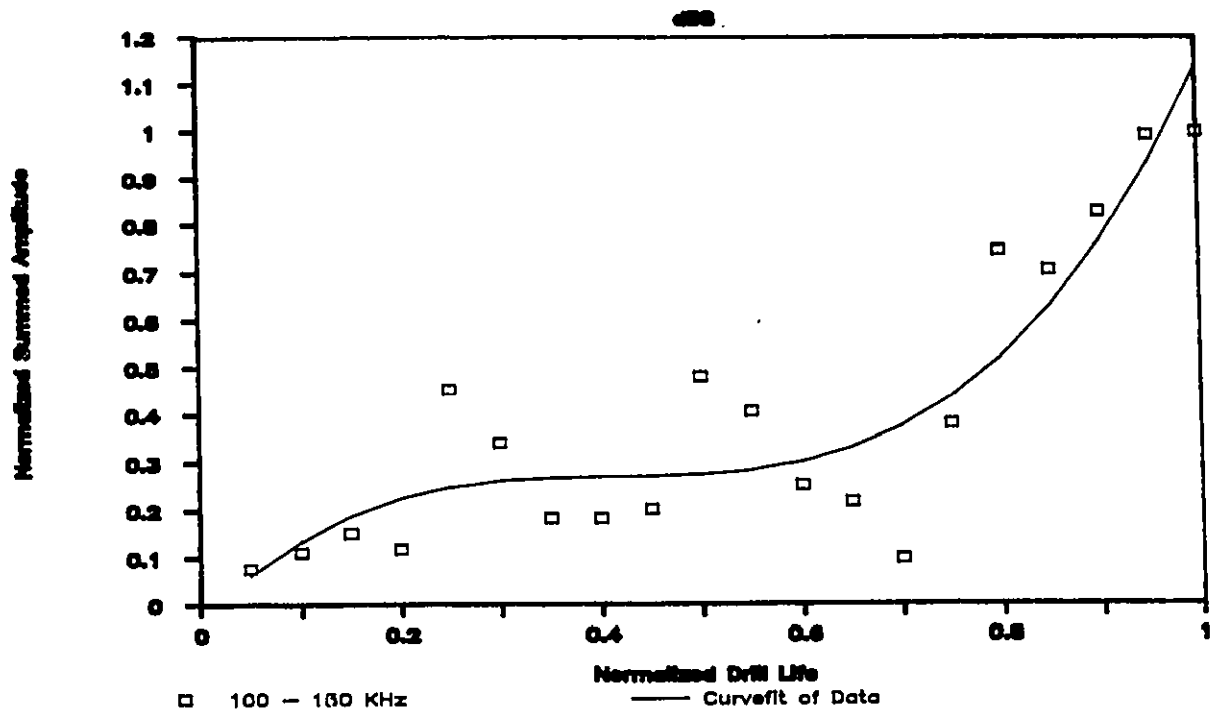


Figure 5.68. Summed amplitude versus drill life - bandwidth 100 - 150 KHz.

Narrowband Analysis

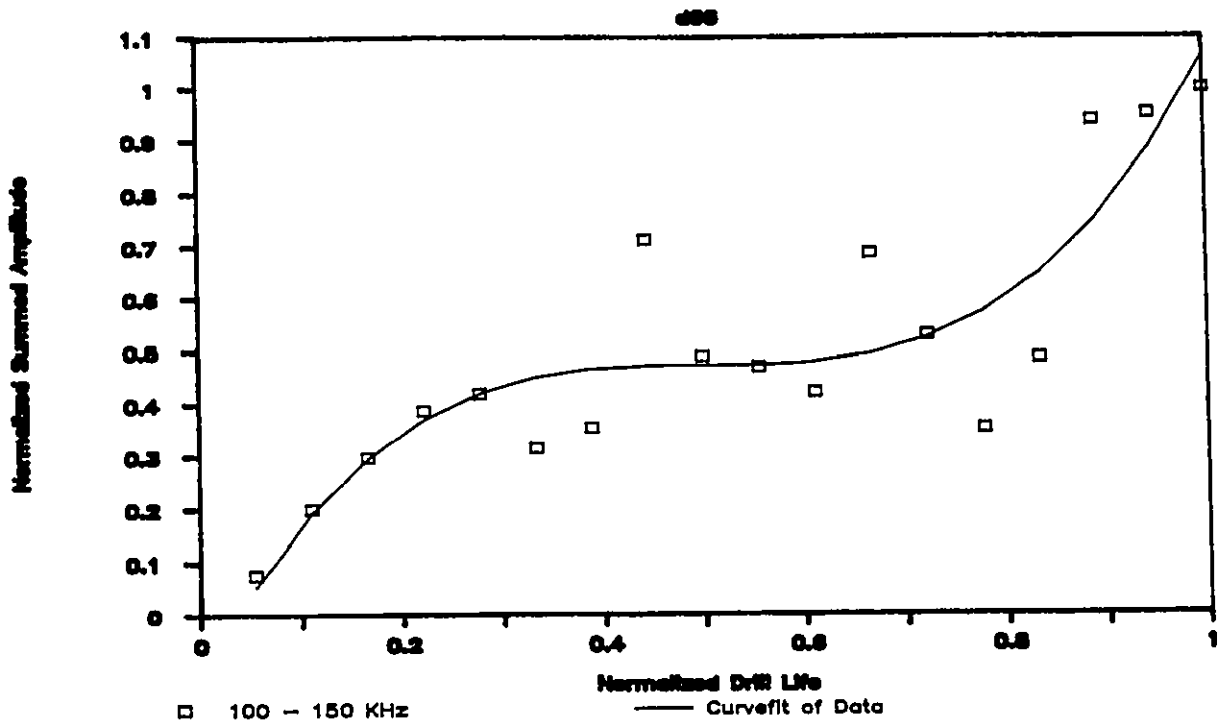


Figure 5.69. Summed amplitude versus drill life - bandwidth 100 - 150 KHz.

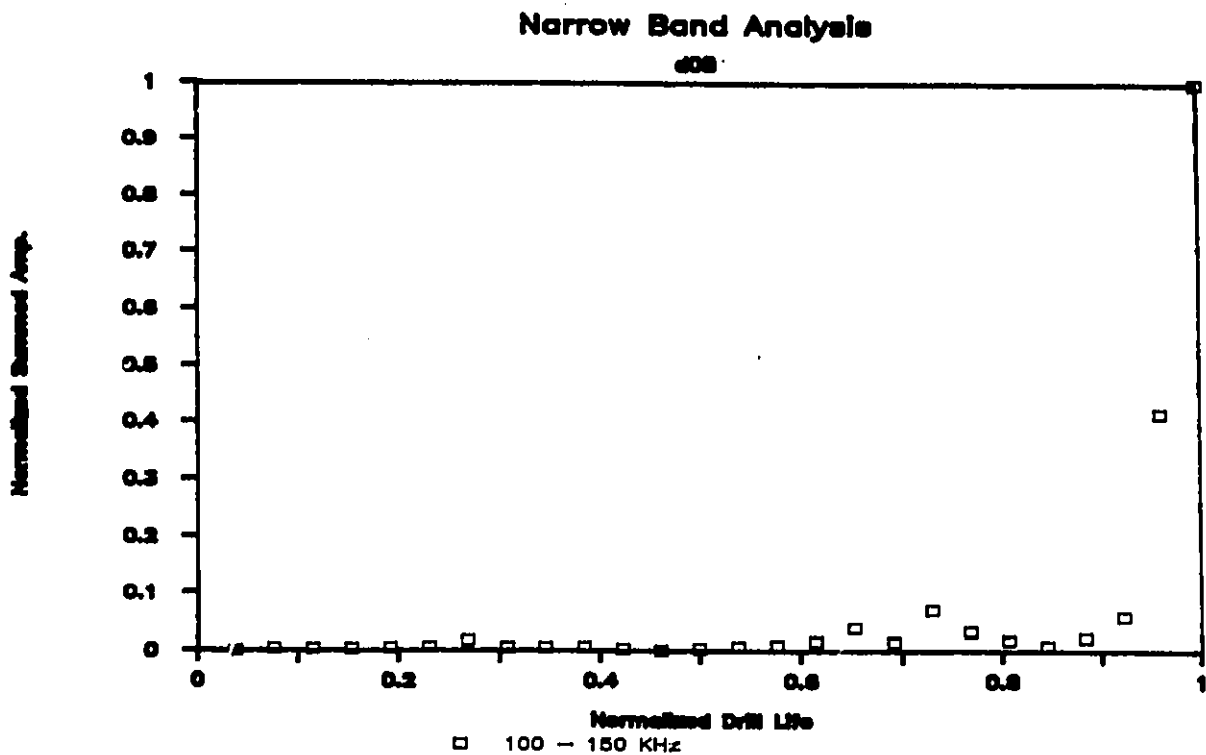


Figure 5.70. Summed amplitude versus drill life - bandwidth 100 - 150 KHz.

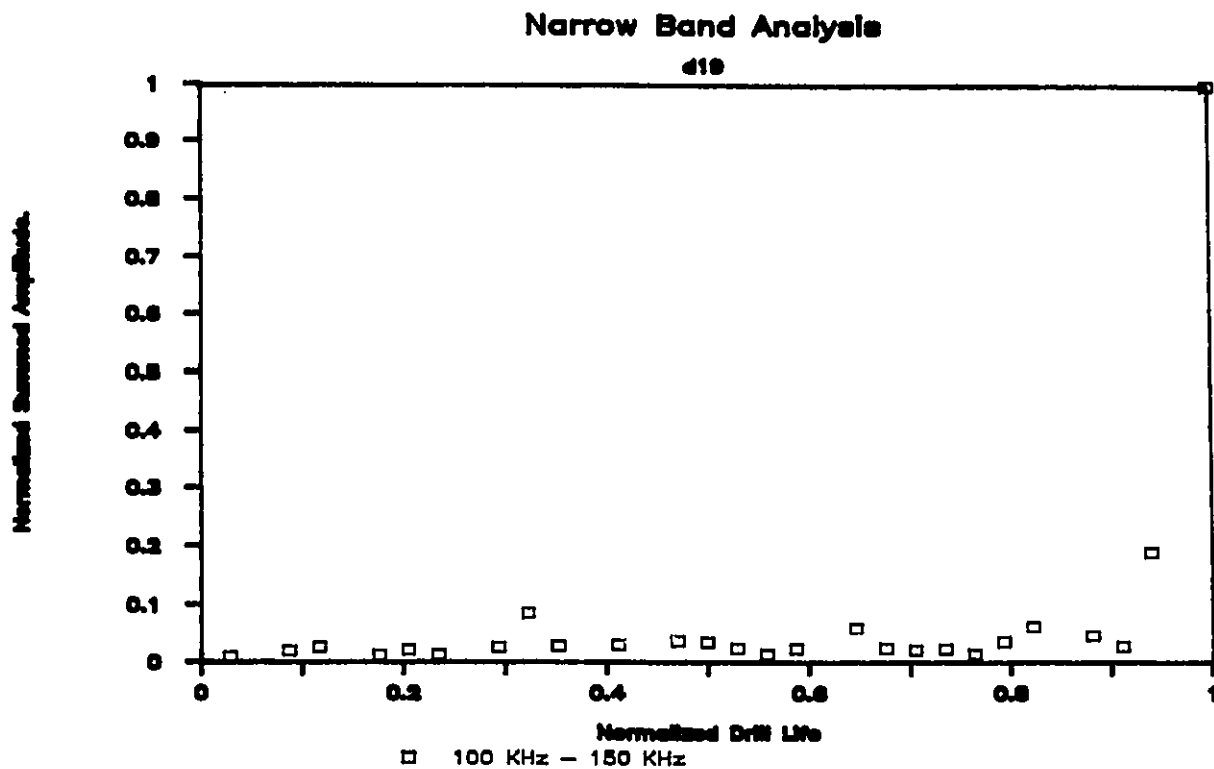


Figure 5.71. Summed amplitude versus drill life - bandwidth 100 - 150 KHz.

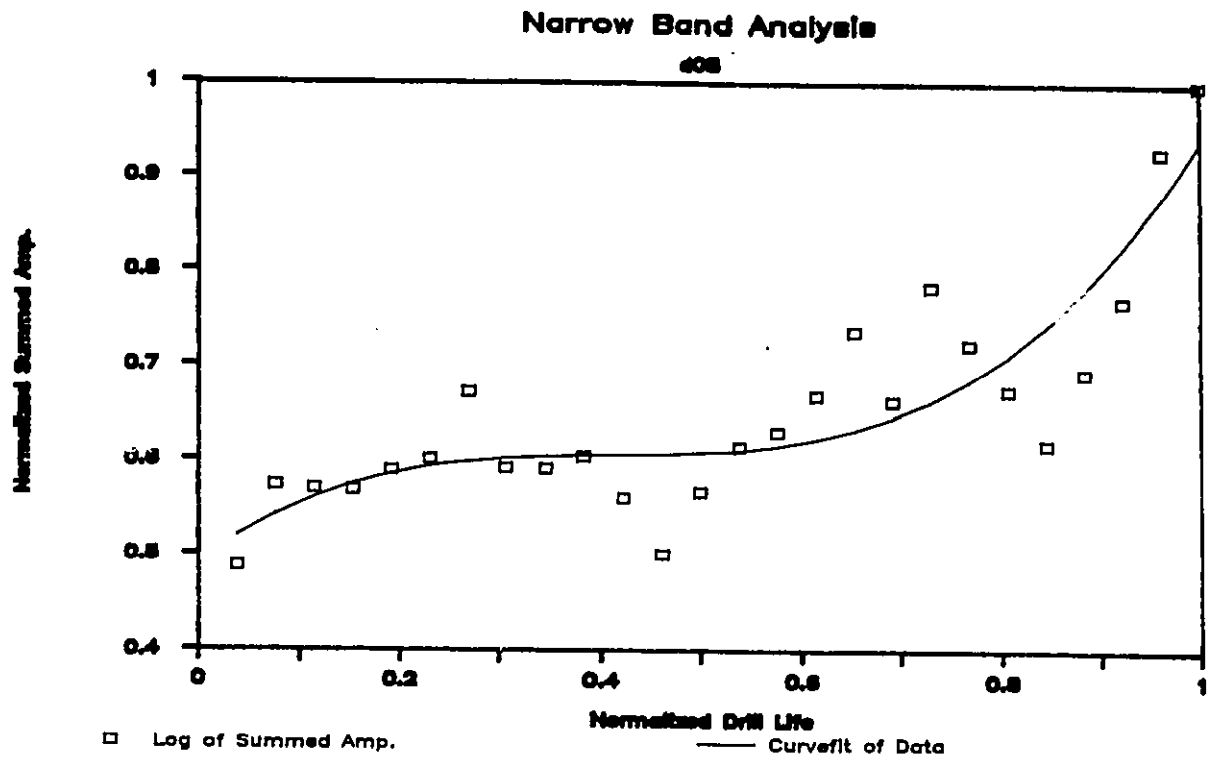


Figure 5.72. Logarithm value of summed amplitude versus drill life.

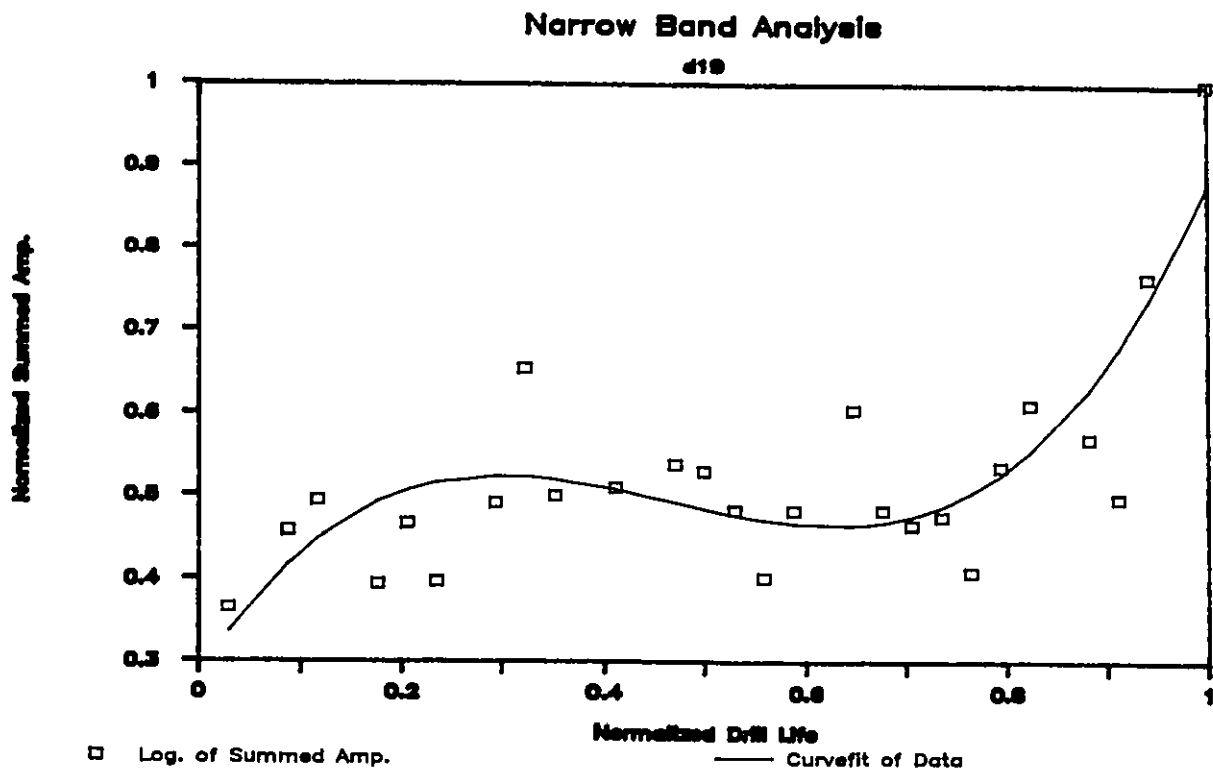


Figure 5.73. Logarithm value of summed amplitude versus drill life.

5.4.6.4. Summary of AE Data Analyses

Acoustic emission data from drilling were monitored with the use of digital oscilloscope, FFT analyzer, TRMS meter and AE counter.

Time and frequency domain and statistical analyses were performed for the data captured by the digital oscilloscope. This results show poor correlations between the parameters and drill wear. However, in view of very short observations of analyzed data, equivalent to 0.016 seconds of drilling time, the results are encouraging. Therefore, with improvements in data capturing capacity, the results can be significantly improved.

TRMS of the AE data shows relatively good correlations against normalized drill life. However, the results did not provide enough repeatability and sufficiently high degree of correlation. It was observed that high amplitudes due to unwanted events, such as chip breakage, severely affected the results despite the short duration of the events.

Most consistent results were obtained when the AE count was employed as a parameter for monitoring the drill condition. The trend of the graph of the AE count against drill life is very similar to that of drill wear versus drill life. Therefore, measurements of AE counts during drilling is considered to be the most promising method of monitoring the condition of drills.

CHAPTER 6

MODEL

In this chapter, a general drill life equation which is capable of calculating and predicting the drill life for the desired drilling speed and feed, is developed by means of the existing drill life equation and experimental results. The polynomial equation of AE counts against drill life is also developed utilizing the least square curvefit program. The changing of the slope of AE count curve with respect to drill life is calculated by differentiating the equation of the AE count curve, and the warning point of the drill failure is predicted by the change of its slope.

Taylor's tool life equation, which is one of the most important empirical relationships in the history of metal cutting, was derived by F.W. Taylor in 1907 as:

$$V * T^{\alpha} = C_T \quad (40)$$

Some modifications of this equation have been used since then. In 1967, Singpurwalla[78] developed a relationship between the variable factors in drilling and drill life. From his experimental results, he developed a logarithmic relationship between the drill life and $V^2 * F$ in the form:

$$T * (V^2 * F)^c = k \quad (41)$$

where

T : drill life

V : cutting speed

F : feed and

C_T , c and k are constants.

The constants in the equation, c and k , vary with the criteria which influence drill life. In his study, three different criteria of the drill life are defined as follows [87]:

- (a) A change in colour, as indicated by the appearance of a dark-blue end of the drill occupying the depth of the hole drilled.
- (b) A change in sound, as detected by an experienced and objective operator.
- (c) A complete failure, as indicated either by a scream, or radial chatter marks at the bottom of the hole, or a chip-out of the corners of the drill.

In this study, the criterion for the drill failure is defined as complete failure which is the same as those stated in (c) above. However, in this study, repeated drilling interruptions occurred because the drill rotated in the chuck due to excessive wear. Hence, the interruption of drilling due to this rotation is included in the drill failure criteria.

The observed drill life, with different drilling speeds and feeds, are plotted. Because the drill life varied significantly, even at the same drilling conditions, the mean life of the drill under the same drilling conditions, was used in plotting. The mean life of the drill at different V^2F was calculated with the method of a logarithmic transformation of the random variables [88] since the ratio of the standard deviation of the drill life to its

arithmetic mean is greater than 1/3 in these experiments.

A similar logarithmic relationship, as that shown by Singpurwalla[78], was found in this study, as shown in Figures 5.1 and 5.2. The author considers this mean drill life, T , as the expected drill life under the given drilling speed and feed without failure. Coefficients are derived from experimental results with the linearization and linear curvefit procedures as shown in Appendix III.

With the execution of the least square curvefit procedure the expected drill life with respect to cutting speed and feed is derived as:

$$T * (V^2 * F)^{1.72} = 3508 \quad (42)$$

Although the expected drill life with the given cutting speed and feed can be obtained from equation (42), the scattering of the drill life values makes practical applications somewhat unsatisfactory. Some parameters which can monitor the condition of the drill from the initial drilling to imminent failure are definitely needed for practical applications. As one of those parameters, the relationship between AE count rate and the drill life is found from experimental results as the following polynomial:

$$\zeta = \alpha_1 * h^3 + \alpha_2 * h^2 + \alpha_3 * h + \alpha_4 \quad (43)$$

where ζ is the normalized count rate of the acoustic emission signal during drilling, h is the normalized drill life and α are the constants which are determined by the polynomial curve fitting procedure by means of the method of least squares. The normalized

drill life is defined as the number of actual drilled holes divided by the number of drilled holes at the drill failure.

The polynomial relationship between the count rate and the drill life has very distinct characteristics which are not evident from the single edge cutting process. Although there are some differences in the coefficients of equations, very distinct trends, similar to those obtained for drill wear, are observed. Initially a rapid increase of counts is followed by a gradual levelling off or decrease and finally a rapid increase in counts close to the drill failure; this is called type I. However, some of the results show very small changes in the slope until very close to the drill breakage; this is called type II. Observations were made to figure out the different types of AE count curves, particularly in the types of drill failure. It was clearly observed that the AE count curves against normalized drill life exhibiting the trend of type I correspond to drill breakage, while those of type II existed when the drill failure was caused by excessive wear, as shown in table 6.1.

In addition to the two different trends of curves, the values of intercepts to the Y axis of the graphs also varied with the different drills. To determine the causes of these differences, the raw data of the first few initial holes of each drill were studied. Although the recalled data from the storage disk represent very short periods of drilling, in most of the cases the intercept was low when the data was of the continuous type, while it was high with the burst type signals.

From the observations of the causes of different types of AE count curve shapes and different values of intercept it was concluded that type I curves represent the drill life criteria defined in this study. The changes of the value of intercept are not considered to be very important in monitoring the condition of drills. Therefore, the author considers that the polynomial trend with drill failure of type I provides the best indication of the drill condition within the expected drill life.

Figure 6.1 shows the curves of the AE count versus normalized drill life of for various drills, which are detailed in Figures 5.10 to 5.20. Table 6.2 shows the values of the coefficients of the equation (49) from 13 drills, which were obtained from the least square curvefit program. The trend shape, which was obtained by averaging values for all drills, is represented by the red points.

Drill#	Intercept	AE Signal	Type of Curve	Type of Fail
1	0.01	C	I	I
2	0.12	C	I	I
3	0.04	C	I	I
4	0.11	B	I	I
5	0.03	C	I	I
6	0.35	B	I	I
7	0.37	B	I	I
8	0.30	C	I	I
9	0.30	B	I	I
10	0.09	C	I	I
11	0.30	B	I	I
12	0.01	C	I	I
13	0.28	B	II	II
14	0.08	C	II	II

Note:

Type of failure (1) I : Breakage.
(2) II : Excessive wear.

Type of AE signal (1) C : Continuous and low amplitude.
of initial drilling (2) B : Burst and high amplitude.

Type of curve (1) I & II : Described in the results.

Table 6.1. Type of drilling data at the initial drilling and type of drill failure.

No. of drill	α_1	α_2	α_3	α_4	Correlation Coefficient [r]
1	5.645	-9.415	5.101	-0.264	0.97
2	3.040	-3.286	1.031	0.155	0.95
3	5.118	-6.979	2.651	0.045	0.90
4	4.078	-5.861	2.431	0.314	0.73
5	3.699	-4.729	1.560	0.202	0.83
6	4.330	-5.430	1.779	0.072	0.89
7	8.180	-12.999	5.872	-0.224	0.90
8	3.211	-4.187	1.699	0.041	0.88
9	3.726	-5.752	2.854	0.248	0.92
10	1.938	-2.408	1.391	0.131	0.97
11	4.753	-6.061	1.978	0.207	0.88
12	5.670	-7.490	2.898	0.013	0.97
13	8.224	-12.932	5.981	-0.289	0.92

Table 6.2. Coefficients of AE count equations.
where $\zeta = \alpha_1 * h^3 + \alpha_2 * h^2 + \alpha_3 * h + \alpha_4$

The general equation of the AE count against drill life was obtained by averaging the above coefficients as follows:

$$\zeta = 4.894h^3 - 6.994h^2 + 3.021h + 0.012 \quad (44)$$

To observe the general drill life in terms of AE count, the resultant curve from Figure 6.1, plotted in red, was replotted as the drill life versus normalized AE count, as shown in Figure 6.2. The normalized drill life, equation (43), was rewritten as a homogeneous equation (45) to utilize the general mathematical procedure to solve the third degree polynomial equations.

$$\alpha_1 * h^3 + \alpha_2 * h^2 + \alpha_3 * h + \beta_0 = 0 \quad (45)$$

where $\beta_0 = \alpha_4 - \zeta$

The normalized drill life h in terms of the normalized AE count, ζ , was obtained by using the general mathematical procedure of

solving third degree polynomial equation 43 as follows:

$$h = y + 0.433 \quad (46)$$

where y is supplemental equation to solve third degree polynomial equation, as shown in Appendix IV.

However, the equation (46) has to be justified for every calculation to get the real value because of the equation is third degree of polynomial.

Another attempt was made to get a single equation that expresses drill life as a function of AE count. Equation (47) was obtained with the use of a curvefit program to the drill life versus AE count data.

$$h = 1 - e^{(-5.658 * \zeta^{2.375})} \quad (47)$$

However, the degree of correlation of the curvefit to the equation is relatively low. Therefore, only a rough approximation for the drill life h, was obtained with the use of a single equation in the validating procedure.

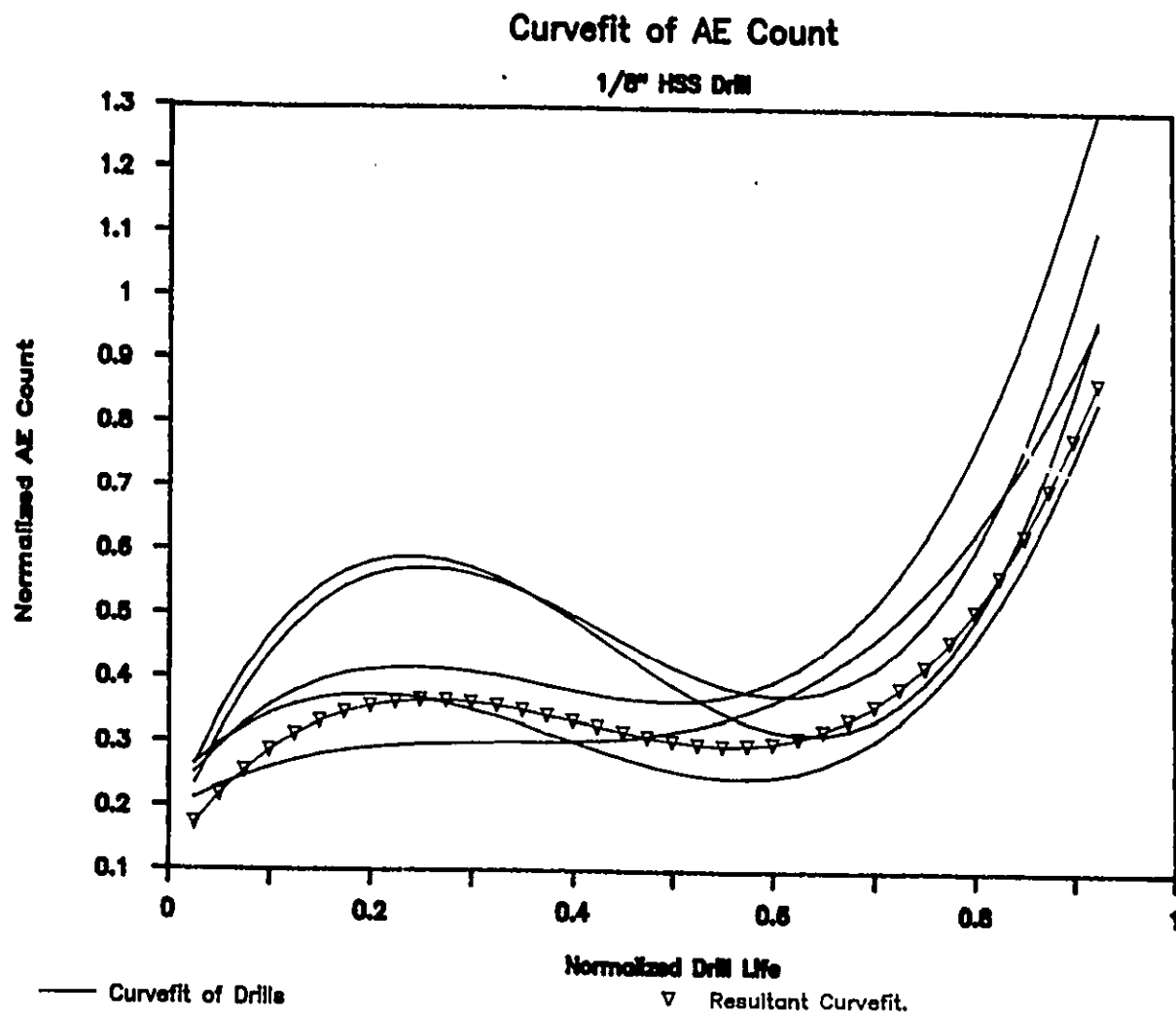


Figure 6.1. Resultant AE count curve versus drill life.

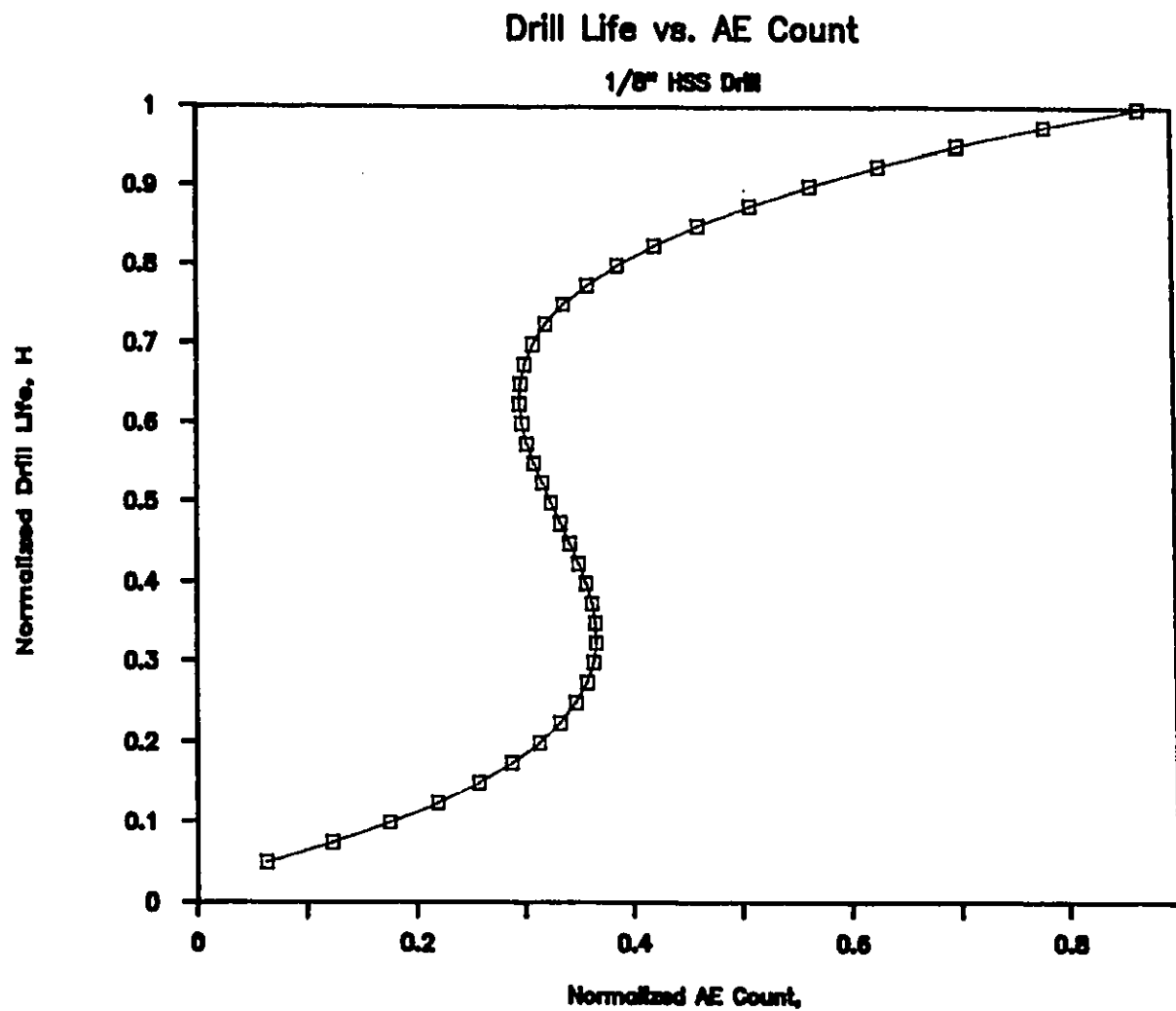


Figure 6.2. A plot of drill life versus AE count.

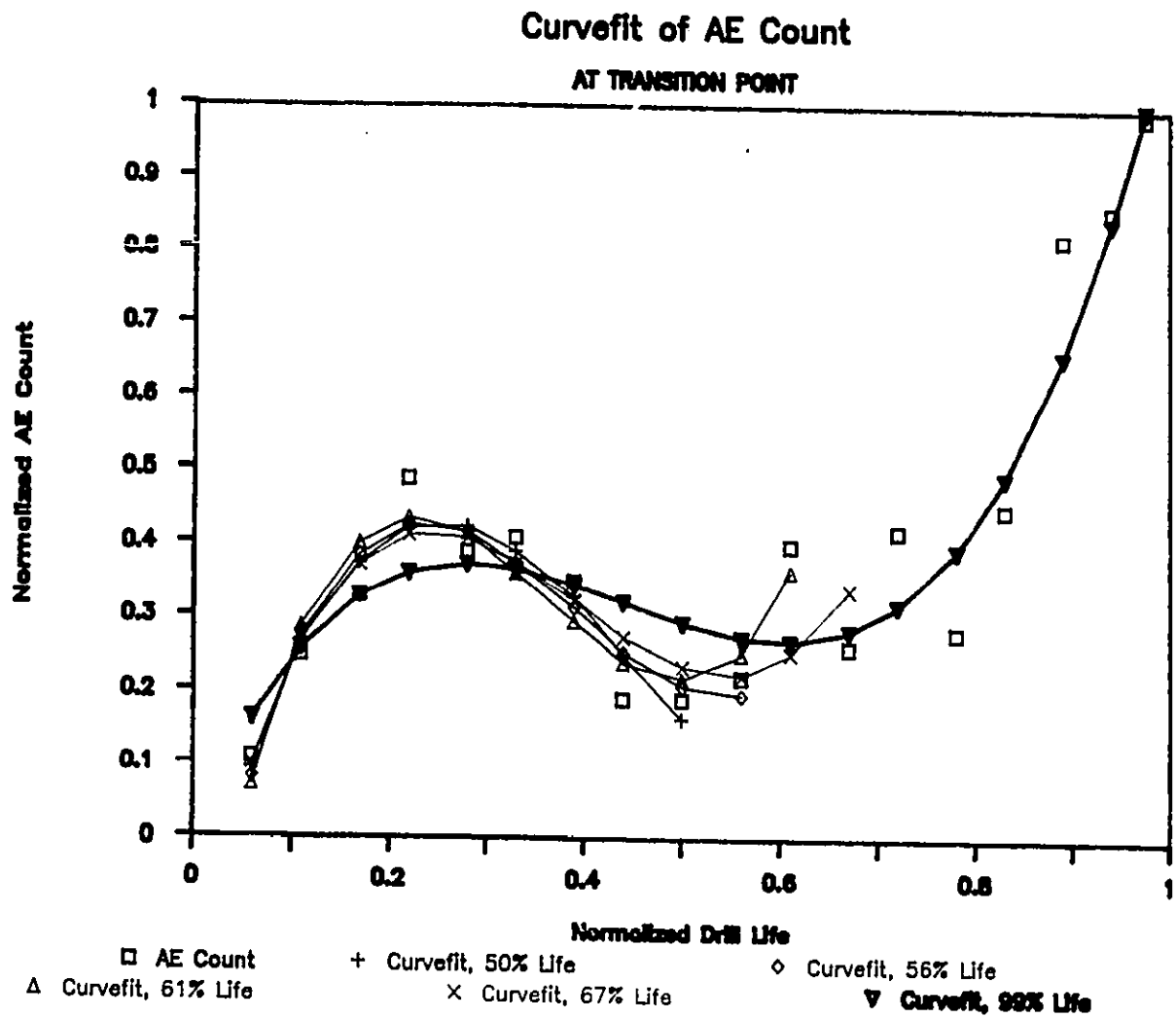


Figure 6.3. Transition of the slope of AE count curve against drill life.

The determination of the level for the warning command to prevent drill failure still remains a problem. To solve it, the changing of the slope of the AE count with the increase of the number of drilled holes was studied. According to Figures 5.10 to 5.21, in most of cases the slope is positive at the beginning of drilling and then changes to negative. Subsequently the slope changes to a high positive value when the drill approaches failure. The continuous observation of the changing slope might be useful for determining the warning to prevent the drill failure. The AE count equation (43), was differentiated to calculate the slope of the AE count curve as follows:

$$d\zeta/dh = 3\alpha_1 * h^2 + 2\alpha_2 * h + \alpha_3 \quad (48)$$

where ζ is the count rate of acoustic emission signal during drilling, h is the normalized drill life and α are the constants determined by the polynomial curve fitting. And then the slope of AE count curve was calculated after every drilling. In order to indicate the trend of the gradient at a particular point in normalized drill life, the curve fitting procedure was performed on measurements for one particular drill up to that point, i.e. in Figure 6.3 up to 50%, 56%, 61%, 67% and 99% of normalized life respectively.

Normalized Drill Life	α_1	α_2	α_3	α_4	$d\zeta/dh$
0.50	1.22	-3.54	2.63	-0.15	-0.43
0.55	2.81	-5.91	3.51	-0.21	-0.23
0.61	4.99	-8.85	4.49	-0.26	-0.03
0.67	4.14	-7.34	3.70	-0.16	0.48
0.72	4.88	-8.15	3.88	-0.15	0.96
0.78	3.53	-5.99	2.88	-0.04	1.64
0.83	6.08	-9.17	3.96	-0.12	2.32
0.89	5.78	-8.56	3.59	-0.07	3.25
0.94	6.02	-8.43	3.37	-0.03	4.13
0.99	6.20	-8.22	3.14	+0.01	4.80

Table 6.3. Coefficient of AE count curve and slope
where $\zeta = \alpha_1 * h^3 + \alpha_2 * h^2 + \alpha_3 * h + \alpha_4$

As shown in Table 6.3, the slope changes from negative to positive which is referred to as the transient point in this study, at 60 percent of drill life. Comparisons were made to the Figure 6.3 which shows the AE count versus normalized drill life. Starting with the gradual increase at the 60 percent of normalized drill life, the AE count changed to a rapid increase at 80 percent of normalized life until drill failure. Therefore, the warning signal of drill failure should be given at the point which has the same magnitude of the previous peak P_1 , as shown in Figure 6.3, after the slope changes from negative to positive.

An evaluation of the characteristics of AE count equation by means of the slope change suggested that the condition of the drill should be very carefully monitored from the point where the slope of the AE count curve changes from negative to positive, which is called the transient point.

Therefore, the drill life equation is derived from the transient point to the drill breakage by means of the least square curvefit, with the following result:

$$h = 1 - e^{(-5.441 * \zeta^{1.609})}, \text{ where } \zeta > 0.6 \quad (49)$$

This equation permits the determination of the warning level for the drill failure.

CHAPTER 7

CONCLUSIONS

From the assessment of the obtained results the following conclusions have been reached:

1. There are three potential descriptors for monitoring the drill performance by means of acoustic emission signals, namely: AE count rate, TRMS and bandwidth amplitude.
2. From the characteristic curves of these parameters against drill life it is evident that the AE count produces most consistent results.
3. The characteristic curves are composed of three distinct stages, a rapid increase during initial drilling, a levelling off or decrease stage, which is then followed by a rapid increase when drill failure is imminent. This trend of the curves is consistent with the progressive drill wear, which is the direct parameter of drill life. This distinct shape of the curves is assumed to be caused by the production tolerances of the drills, which include the run-out tolerance of the drill edge.
4. A characteristic equation of drill life in terms of AE count was derived by utilizing the least square third degree polynomial curvefit of experimental data. This equation can predict the drill condition in terms of the

AE count.

5. The point, at which the slope of the third degree fit curves of the AE count is changing from negative to positive, which is called the transient point in this study, was also found to be a useful parameter for warning of the impending drill failure. A rapid increase towards failure always started after that point on the characteristic curve. It was observed mostly after 60 percent of drill life.
6. The observation of amplitude change of time domain signal from drilling is not useful to monitor the drill condition related to the progressive drill wear. But the rotation of the drill in the tool holder or imminent drill failure can be detected by observing significant magnitude fluctuations or the instantaneous disappearance of the time domain signal.
7. In the statistical analyses of the time domain signal (equivalent to 0.016 seconds of drilling time), RMS and standard deviation exhibit noticeable degree of correlation to progressive drill wear while skewness and kurtosis produce generally scattered results. The performance of these parameters in drill monitoring is found to be inadequate.
8. The frequency band which provides best indication of progressive drill wear was found to be between 100 to 150 kHz. Practical applications of bandwidth analysis can

not be recommended from this study because of the insufficient data size. The inconsistency of the obtained results and the relatively long processing time may be further impediments to the use of this procedure.

CHAPTER 8

RECOMMENDATIONS

Monitoring drill performance by means of Acoustic Emission is shown in this study to be a promising tool condition monitoring method. However, better results can be obtained with improvements of the data acquisition and processing equipment. The limitations of this study which need to be improved and some suggestions for further research are as follows:

1. In this study, because of the capabilities of available equipment, the maximum duration of the drilling time of acquired AE signals for drilling, for the frequency analysis and statistical analysis, was 0.016 seconds. The consistency of the results can be increased by capturing and storing a longer period of drilling data.
2. The effect of threshold amplitude on the AE count should also be studied in more detail. A proper threshold voltage can be determined by the use of multiple pulse-counters with different threshold amplitudes in monitoring the same drilling sequence.
3. A multi channel data processing hardware and software in a computer, which can process the AE count, TRMS and store the data at the same time, would compensate for the disadvantages of acquiring basic data at different instances of the drilling cycle. This would improve the

reliability of the results.

4. The transient point was used for the warning of the beginning of rapid drill wear. More extensive experiments should be performed to find out the critical level of AE counts at which the drilling should be stopped.
5. More extensive experiments should be performed with various drill sizes and workpiece materials, under a larger range of operating conditions, in order to establish an adequate knowledge-base for the development of an intelligent system in the future.

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APPENDIX I.

**A BIBLIOGRAPHY OF
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APPENDIX II
COMPUTER PROGRAMS

<< Drill condition monitoring >>

```

'
' $DYNAMIC
DECLARE SUB statres (rd!(), n!)           'Statistical analysis
DECLARE SUB datastore (dstsel)           'Store data
DECLARE SUB counter (AE!(), countnp)     'Pulse count
DECLARE SUB fluke (rdrms(), flukemp)
DECLARE SUB sd375 (x!(), spectnp)
DECLARE SUB prowler (rd!(), n)
DECLARE SUB stfft (x!(), inv!(), n!)     'Sande-Tukey FFT
DECLARE SUB windbox (px1!, py1!, px2!, py2!) 'Store portion of graphic screen
DECLARE SUB censtr (row!, strg$)         'Put string in center of screen
DECLARE SUB retenter (row, col)
DECLARE SUB plot (x!(), n)               'Plotting
DECLARE SUB errcode (code)               'Type of error encounter
DIM SHARED mean, std, sk, kur, rmsrd, rmsfd, divs, yy(1)
DIM SHARED pg%, gsc% (1), sb%, gsc1% (1), CB%, code$(20), graphflag$
DIM SHARED xmin, xmax, ymin, ymax
DIM SHARED spectnp, flukemp, countnp, n
DIM SHARED x(8192), rd(8192), rdrms(500), AE(500)
'
'==== Select Graphic driver and Input drilling data ====
'
LHK: graphflag$ = "0": ON ERROR GOTO errtrap1
CLS : LOCATE 1, 2: FOR i% = 2 TO 79: PRINT ":", NEXT i%
FOR i = 2 TO 24: LOCATE 1, 2: PRINT ":", LOCATE i, 79: PRINT ":", NEXT i
LOCATE 25, 2: FOR i% = 2 TO 79: PRINT ":", NEXT i%
strg$ = "<< DRILL CONDITION MONITORING >>": CALL censtr(3, strg$)
LOCATE 5, 2: FOR i% = 2 TO 79: PRINT ":", NEXT i%
LOCATE 10, 28: PRINT "Graphic card selection : "
LOCATE 11, 28: PRINT "-----"
LOCATE 12, 28: PRINT "1. Hercules garphic card ?"
LOCATE 13, 28: PRINT "2. Color graphic card (CGA)?"
LOCATE 14, 28: PRINT "3. EGA ?"
LOCATE 15, 28: PRINT "4. None ?"
LSP: LOCATE 17, 28: INPUT "Selection (1/2/3/4) :", gcsel$: gcsel = VAL(gcsel$)
IF gcsel < 1 OR gcsel > 4 THEN GOTO LSP
IF gcsel = 4 THEN GOTO proc
CB% = 1
IF gcsel = 1 THEN pg% = 3
IF gcsel = 2 THEN pg% = 2
IF gcsel = 3 THEN pg% = 9: CB% = 2
FOR i = 7 TO 20: LOCATE i, 3: PRINT SPACES(75): NEXT i
strg$ = "Please Enter Drilling Data:": CALL censtr(9, strg$)
LOCATE 11, 15: INPUT "Drill number :"; dnum
LOCATE 12, 15: INPUT "Drill size [in.] :"; dsiz
LOCATE 13, 15: INPUT "Drill material :"; dmat$
LOCATE 14, 15: INPUT "Workpiece material :"; wmat$
LOCATE 15, 15: INPUT "Speed [RPM] :"; dspeed
LOCATE 16, 15: INPUT "Feed rate [in/Rev.] :"; dfeed
SCREEN pg%
'
'==== Main menu ====
'
rstart:
CLS : VIEW PRINT 1 TO 25
ON ERROR GOTO errtrap2
mmenu: GOSUB logo: LINE (10, 135)-(490, 445), 0, BF
LOCATE 6, 13: PRINT "Main menu"
LOCATE 7, 10: PRINT "===== "
LOCATE 9, 5: PRINT "1. Data acquisition ?"
LOCATE 10, 5: PRINT "2. Data analysis ?"
LOCATE 11, 5: PRINT "3. Data presentation ?"
LOCATE 12, 5: PRINT "4. Data storage ?"
LOCATE 13, 5: PRINT "5. Data reduction (Diagnostic) ?"
LOCATE 14, 5: PRINT "6. Exit ?"
m1: LOCATE 16, 5: INPUT "Selection (1-6) :"; mmsel$: mmsel = VAL(mmsel$)
IF mmsel < 1 OR mmsel > 6 THEN GOTO m1
IF mmsel = 6 THEN GOTO proc
IF mmsel = 1 THEN GOSUB dacq
IF mmsel = 2 THEN GOSUB danalysis
IF mmsel = 3 THEN GOSUB dpresent
IF mmsel = 4 THEN GOSUB dstorage
IF mmsel = 5 THEN GOSUB ddiag
GOTO mmenu
'

```

```

,      ==== Data acquisition ====
,
dacq: LINE (10, 135)-(490, 445), 0, BF
LOCATE 6, 6: PRINT "DATA ACQUISITION"
LOCATE 8, 6: PRINT "1. Pulse counter ?"
LOCATE 9, 6: PRINT "2. Fluke RMS voltmeter ?"
LOCATE 10, 6: PRINT "3. Prowler ?"
LOCATE 11, 6: PRINT "4. SD375 ?"
LOCATE 12, 6: PRINT "5. Retrieve data ?"
LOCATE 13, 6: PRINT "6. Return ?"
dacq11: LOCATE 15, 6: INPUT "Selection (1-6) :"; dacqsel$: dacqsel = VAL(dacqsel$)
IF dacqsel < 1 OR dacqsel > 6 THEN GOTO dacq11
IF dacqsel = 6 THEN RETURN
code = 10
IF dacqsel = 1 THEN CALL counter(AE(), countnp)
IF dacqsel = 2 THEN CALL fluke(rdms(), flukemp)
IF dacqsel = 3 THEN CALL prowler(rd(), n)
IF dacqsel = 4 THEN CALL sd375(x(), spectnp)
IF dacqsel = 5 THEN code = 7: GOSUB retdata
RETURN
,
,      ==== Data analysis ====
,
danalysis: LINE (10, 135)-(490, 445), 0, BF
LOCATE 6, 7: PRINT "DATA ANALYSIS"
LOCATE 8, 7: PRINT "1. Time domain ?"
LOCATE 9, 7: PRINT "2. Frequency domain ?"
LOCATE 10, 7: PRINT "3. Return ?"
LOCATE 12, 7: INPUT "Selection (1-3) :"; dasel$: dasel = VAL(dasel$)
IF dasel = 3 THEN RETURN
code = 3: IF n = 0 THEN GOTO errtrap2
IF dasel = 1 THEN CALL statres(rd(), n)
IF dasel = 2 THEN
    LOCATE 11, 45: PRINT "Please, wait ...."
    FOR i% = 1 TO n: x(i%) = rd(i%):
    x(i%) = x(i%) * .5 * (1 - COS((6.283185 * (i% + .5)) / n))
    NEXT i%
    inv = 0: CALL stfft(x(), inv, n): spectnp = n / 2
END IF
RETURN
,
,      ==== Data presentation ====
,
dpresent: LINE (10, 135)-(490, 445), 0, BF
LOCATE 6, 6: PRINT "DATA PRESENTATION"
LOCATE 8, 6: PRINT "1. Plot pulse count ?"
LOCATE 9, 6: PRINT "2. Plot fluke RMS ?"
LOCATE 10, 6: PRINT "3. Plot prowler raw data ?"
LOCATE 11, 6: PRINT "4. Plot Frequency spectrum ?"
LOCATE 12, 6: PRINT "5. Print Stat. result ?"
LOCATE 13, 6: PRINT "6. View plot ?"
LOCATE 14, 6: PRINT "7. Return ?"
dp11: LOCATE 16, 6: INPUT "Selection (1-7) :"; dpsel$: dpsel = VAL(dpsel$)
IF dpsel < 1 OR dpsel > 7 THEN GOTO dp11
IF dpsel = 7 THEN RETURN
code = dpsel
IF dpsel = 5 THEN
    IF divs = 0 THEN GOTO errtrap2
    ymax = 0
    FOR i% = 1 TO divs: IF yy(i%) > ymax THEN ymax = yy(i%)
    NEXT i%
    xmin = 1: xmax = divs: ymin = 0: CALL plot(yy(), divs)
    LOCATE 20, 1: PRINT SPACES(75): LOCATE 21, 5: PRINT SPACES(70)
    LOCATE 20, 10: PRINT "Mean ="; mean; TAB(30); "Std. ="; std; TAB(53); "Skew ="; sk
    LOCATE 21, 10: PRINT "Kur. ="; kur; TAB(30); "RMSrd ="; rmsrd; TAB(53); "RMDfd ="; rmsfd
    CALL retenter(23, 0)
END IF
IF dpsel = 6 THEN
    IF graphflag$ = "0" THEN GOTO errtrap2
    GOSUB imgput
END IF
IF dpsel = 1 THEN
    IF countnp = 0 THEN GOTO errtrap2
    y8 = -1E+07
    FOR i% = 1 TO countnp
        IF AE(i%) > y8 THEN y8 = AE(i%)
    NEXT i%
    ymin = 0: ymax = y8 * 1.5: xmin = 1: xmax = countnp: CALL plot(AE(), countnp)

```



```

ELSEIF dpsel = 2 THEN
  IF flukemp = 0 THEN GOTO errtrap2
  y8 = -1E+07
  FOR i% = 1 TO flukemp: IF rdrms(i%) > y8 THEN y8 = rdrms(i%)
  NEXT i%
  ymin = 0: ymax = y8 * 1.5: xmin = 1: xmax = flukemp: CALL plot(rdrms(), flukemp)
ELSEIF dpsel = 3 THEN
  IF n = 0 THEN GOTO errtrap2
  y8 = -1E+07: y7 = 1E+07
  FOR i% = 1 TO n
    IF rd(i%) > y8 THEN y8 = rd(i%)
    IF rd(i%) < y7 THEN y7 = rd(i%)
  NEXT i%
  ymin = y7: ymax = y8: xmin = 1: xmax = n: CALL plot(rd(), n)
ELSEIF dpsel = 4 THEN
  IF spectnp = 0 THEN GOTO errtrap2
  SCREEN pg$: x7 = 1E+07: x8 = -1E+07
  FOR i% = 1 TO n / 2 - 1
    IF x(i%) > x8 THEN x8 = x(i%)
    IF x(i%) < x7 THEN x7 = x(i%)
  NEXT i%
  LINE (550, 135)-(990, 445), 0, BF
  LOCATE 5, 45: PRINT "INPUT PLOTTING INFO.:"
  LOCATE 7, 45: PRINT "Xmin, Xmax =": TAB(59); USING "#####.##"; 0; TAB(70); n / 2
  LOCATE 8, 45: PRINT "Ymin, Ymax =": TAB(59); USING "#####.##"; x7; TAB(70); x8
  dpl2: LOCATE 10, 45: INPUT "Xmin, Xmax =", xmin, xmax
  LOCATE 11, 45: INPUT "Ymin, Ymax =", ymin, ymax
  LOCATE 13, 45: INPUT "Satisfy (y/n) ?": ans
  IF ans = "n" OR ans = "N" THEN GOTO dpl2
  CALL plot(x(), n / 2 - 1)
END IF
RETURN
'
'      ==== Data storage ====
'
dstorage: LINE (10, 135)-(490, 445), 0, BF
dst1: LOCATE 6, 7: PRINT "DATA STORAGE"
LOCATE 8, 7: PRINT "1. Pulse count ?"
LOCATE 9, 7: PRINT "2. Fluke RMS ?"
LOCATE 10, 7: PRINT "3. Prowler raw data ?"
LOCATE 11, 7: PRINT "4. Frequency spectrum ?"
LOCATE 12, 7: PRINT "5. Statistical results ?"
LOCATE 13, 7: PRINT "6. return"
LOCATE 15, 7: INPUT "selection (1-6) :": dstsel$: dstsel = VAL(dstsel$)
IF dstsel < 1 OR dstsel > 6 THEN GOTO dst1
IF dstsel = 6 THEN RETURN
code = dstsel
ON dstsel GOTO edst1, edst2, edst3, edst4, edst5
edst1: IF countnp = 0 THEN GOTO errtrap2 ELSE GOTO callst
edst2: IF flukemp = 0 THEN GOTO errtrap2 ELSE GOTO callst
edst3: IF n = 0 THEN GOTO errtrap2 ELSE GOTO callst
edst4: IF spectnp = 0 THEN GOTO errtrap2 ELSE GOTO callst
edst5: IF divs = 0 THEN GOTO errtrap2 ELSE GOTO callst
callst: CALL dststore(dstsel)
RETURN
'
'      ==== Data reduction ====
'
ddiag:
strg$ = "This option is not install yet !!": CALL censtr(21, strg$)
CALL retenter(23, 0)
RETURN
'
'      ==== Retrieve raw data ====
'
retdata: LINE (510, 135)-(990, 445), 0, BF
LOCATE 6, 45: INPUT "Filename :", Nam$
LOCATE 7, 45: INPUT "Drive (A/B/C) :", dr$
retl1: LOCATE 9, 45: INPUT "Satisfy (Y/N) ": ans: ans = UCASE$(ans)
IF ans = "Q" THEN RETURN
IF NOT (ans = "Y" OR ans = "N") THEN GOTO retl1
IF ans = "N" THEN GOTO retdata
LOCATE 15, 45: PRINT "Please, wait ....."
OPEN dr$ + ":" + Nam$ FOR INPUT AS #1
INPUT #1, n, nc: FOR i% = 1 TO n: INPUT #1, x(i%): rd(i%) = x(i%): NEXT i%
CLOSE #1
RETURN

```

```

logo: SCREEN pg#: WINDOW (0, 0)-(1000, 500): LINE (0, 0)-(1000, 500), 0, BF
LINE (0, 0)-(1000, 500), , B
strg$ = "TOOL CONDITION MONITORING": CALL censtr(2, strg$): LOCATE 2, 72: PRINT "V 1.0"
LINE (0, 450)-(1000, 450): LINE (0, 130)-(1000, 130): LINE (500, 130)-(500, 450)
RETURN

errtrap1: LOCATE 21, 5: PRINT "*** Error 8 - Unmatched graphic driver"
CALL retenter(23, 0)
RESUME LHK
errtrap2: CALL errcode(code)
IF code < 9 THEN RESUME rstart
END

imgput:
SCREEN pg#: CLS : VIEW: WINDOW
IF pg# = 2 THEN PUT (30, 5), gst#
IF pg# = 9 THEN PUT (30, 50), gst#
IF pg# = 3 THEN PUT (10, 5), gst#
ls3: IF INKEY$ <> CHR$(13) THEN GOTO ls3
CLS : RETURN

proc: strg$ = "THAT'S ALL FOLKS": CALL censtr(22, strg$): END

REM $STATIC
SUB censtr (row, strg$) STATIC
strg$ = LTRIM$(strg$): strg$ = RTRIM$(strg$): length = LEN(strg$)
col = 40 - length / 2: LOCATE row, col: PRINT strg$;
END SUB

SUB counter (AE(), countnp) STATIC
'
'      ==== Acquire data from the counter ====
'
LINE (10, 5)-(990, 125), 0, BF
strg$ = "Press 'ENTER' to start Capturing... [ Counter --> IBM XT ]": CALL censtr(21, strg$)
aefl1: IF INKEY$ <> CHR$(13) THEN GOTO aefl1
strg$ = "Press 'S' to stop capturing": CALL censtr(23, strg$)
CALL windbox(200, 150, 800, 300)
LOCATE 13, 28: PRINT "CAPTURING .....RMS from Fluke"
ic = 1: Y = INP(&H303)
aefl3: AS = INKEY$: IF AS = "s" OR AS = "S" THEN GOTO aefl2
x = INP(&H300)
c = INP(&H303)
B = INP(&H302)
A = INP(&H301)
AE(ic) = AE(ic) + A * 2 ^ 16 + B * 2 ^ 8 + c
LOCATE 15, 28: PRINT ic, AE(ic)
ic = ic + 1: GOTO aefl3
aefl2: countnp = ic - 1
END SUB

SUB datstore (dstsel) STATIC
aa$(1) = "Pulse count": aa$(2) = "Fluke RMS": aa$(3) = "Prowler raw data"
aa$(4) = "Frequency spectrum": aa$(5) = "Statistical results"
LINE (510, 135)-(990, 445), 0, BF
LOCATE 6, 45: PRINT "Storing << "; aa$(dstsel); " >>"
dstl1: LOCATE 8, 45: INPUT "Want to store data (y/n) "; an$: an$ = UCASE$(an$)
IF an$ = "Q" THEN GOTO dstes
IF NOT (an$ = "Y" OR an$ = "N") THEN GOTO dstl1
IF an$ = "Y" THEN
dstl2: LOCATE 8, 45: PRINT SPACE$(30): LOCATE 8, 45: INPUT "Filename to store data :", Nam$
LOCATE 9, 45: INPUT "Drive (A/B/C), or Path :", dr$
LOCATE 22, 10: PRINT "<<< Data will be stored on {"; Nam$; " } in Drive "; dr$; " >>>"
dstl3: LOCATE 11, 45: INPUT "OK to save now (Y/N) "; san$: san$ = UCASE$(san$)
IF san$ = "Q" THEN GOTO dstes
IF NOT (san$ = "Y" OR san$ = "N") THEN GOTO dstl3
IF san$ = "N" THEN GOTO dstl2
ELSE
GOTO dstes
END IF
LOCATE 13, 45: PRINT "Please wait....."
OPEN dr$ + ":" + Nam$ FOR OUTPUT AS #1
IF dstsel = 1 THEN
PRINT #1, countnp, 2
FOR i% = 1 TO countnp: PRINT #1, i%, AE(i%): NEXT i%
ELSEIF dstsel = 2 THEN
PRINT #1, flukemp, 2
FOR i% = 1 TO flukemp: PRINT #1, i%, rdrms(i%): NEXT i%

```

```

ELSEIF datsel = 3 THEN
    PRINT #1, n, 1
    FOR i% = 1 TO n: PRINT #1, rd(i%): NEXT i%
ELSEIF datsel = 4 THEN
    PRINT #1, spectnp, 1
    FOR i% = 1 TO spectnp: PRINT #1, x(i%): NEXT i%
ELSE
    PRINT #1, mean, std, sk, kur, rmsrd, rmsfd
END IF
CLOSE #1
datsel: END SUB

SUB errcode (code) STATIC
LINE (10, 5)-(990, 125), 0, BF
code$(1) = "*** Error 1 - No pulse count data available"
code$(2) = "*** Error 2 - No RMS values available"
code$(3) = "*** Error 3 - No raw data available"
code$(4) = "*** Error 4 - No frequency spectrum available"
code$(5) = "*** Error 5 - No statistical results available/Unspecified number of classes"
code$(6) = "*** Error 6 - No PLOT available"
code$(7) = "*** Error 7 - Unsuccessful attempt in retrieving data from file"
code$(8) = "*** Error 8 - No diskette in drive a, Please insert one"
code$(9) = "*** Error 9 - "
code$(10) = "*** Error 10 - Unrecognized error"
LOCATE 21, 3: PRINT code$(code)
CALL retenter(23, 0)
END SUB

SUB fluke (rdrms(), flukemp) STATIC
,
,      ==== Acquire data from Fluke RMS voltmeter ====
,
LINE (10, 5)-(990, 125), 0, BF
strg$ = "Press 'ENTER' to start Capturing... [ FLUKE --> IBM XT ]": CALL censtr(21, strg$)
f11: IF INKEY$ <> CHR$(13) THEN GOTO f11
strg$ = "Press 'S' to stop capturing": CALL censtr(23, strg$)
CALL windbox(200, 150, 800, 300)
LOCATE 13, 25: PRINT "CAPTURING .....RMS from Fluke"
bdname$ = "fluke": CALL ibfind(bdname$, bd%)
CALL ibsic(bd%): v% = 1: CALL IBSRE(bd%, v%)
length% = 8: CALL ibtmo(bd%, length%)
v% = &H61: CALL ibsad(bd%, v%)
count = 1
f13: A$ = INKEY$: IF A$ = "s" OR A$ = "S" THEN GOTO f12
rd$ = SPACE$(12): CALL ibrd(bd%, rd%)
rdrms(count) = VAL(MID$(rd$, 1, 8))
LOCATE i5, 28: PRINT count, rdrms(count): count = count + 1: GOTO f13
f12: count = count - 1
flukemp = count
LINE (200, 150)-(800, 300), 0, BF: PUT (200, 50), gst1%
END SUB

SUB plot (Y(), np)
SCREEN pg%: CLS : VIEW
IF pg% = 2 THEN
    xrange = 630 - 30 + 1: yrange = 195 - 5 + 1
    size = INT(xrange / 8 + 1) * yrange * .5 + 4: REDIM gst%(size)
ELSEIF pg% = 9 THEN
    xrange = 630 - 30 + 1: yrange = 300 - 100 + 1
    size = INT(xrange / 8 + 1) * yrange + 4: REDIM gst%(size)
ELSE
    xrange = 700 - 30 + 1: yrange = 330 - 5 + 1
    size = INT(xrange / 8 + 1) * yrange * 1 / 2 + 4: REDIM gst%(size)
END IF
IF pg% = 2 THEN VIEW (130, 1%)-(532, 148)
IF pg% = 9 THEN VIEW (130, 70)-(532, 220)
IF pg% = 3 THEN VIEW (143, 20)-(605, 258)
WINDOW (0, 0)-(500, 500): LINE (0, 0)-(500, 500), , B
FOR i = 1 TO 5
    FOR jy% = 0 TO 500 STEP 12: PSET (i * 100, jy%): NEXT jy%
    FOR jx% = 0 TO 500 STEP 10: PSET (jx%, i * 100): NEXT jx%
NEXT i
IF pg% = 9 THEN
    LOCATE 16, 11: PRINT ymin: LOCATE 6, 11: PRINT ymax
    LOCATE 18, 16: PRINT xmin: LOCATE 18, 66: PRINT xmax
ELSE
    LOCATE 19, 11: PRINT ymin: LOCATE 2, 11: PRINT ymax
    LOCATE 21, 16: PRINT xmin: LOCATE 21, 66: PRINT xmax

```

```

END IF
PSET (0, 0)
WINDOW (xmin, ymin)-(xmax, ymax)
IF xmin = 0 THEN xmin = 1
FOR j% = xmin TO xmax: LINE -(j%, Y(j%)): NEXT j%
WINDOW: VIEW: graphflag$ = "1"
IF pg% = 2 THEN GET (30, 5)-(630, 195), gsc%
IF pg% = 9 THEN GET (30, 50)-(630, 250), gsc%
IF pg% = 3 THEN GET (30, 5)-(700, 330), gsc%
CALL windbox(50, 20, 950, 80)
CALL retenter(23, 0)
LINE (50, 20)-(950, 80), 0, BF: PUT (50, 20), gsc1%
WINDOW: VIEW
END SUB

SUB prowler (rd(), n) STATIC
'
' ===== Acquire data from Prowler digital oscilloscope =====
'
LINE (510, 135)-(990, 445), 0, BF
LOCATE 6, 45: INPUT "Segment to transfer (1-8) :", nseg
LOCATE 7, 45: INPUT "Range [mV] :", r
strg$ = "Press 'ENTER' to start Capturing.. [ PROWLER ==> IBM XT ]": CALL censtr(21, strg$)
l4: IF INKEY$ <> CHR$(13) THEN GOTO l4
LOCATE 10, 45: PRINT "CAPTURING Data ....."
LOCATE 21, 5: PRINT SPACES(70)
bdname$ = "prowler": CALL ibfind(bdname$, bd%)
CALL ibsic(bd%): v% = 1: CALL IBSRE(bd%, v%)
length% = 11: CALL ibtmo(bd%, length%)
wrt$ = "T" + CHR$(255): CALL ibwrt(bd%, wrt%)
FOR i = 1 TO 3000: NEXT i
rd1$ = ""
FOR i = 1 TO nseg
rd$ = SPACES(4132): CALL ibrd(bd%, rd$): rd1$ = rd1$ + rd$
NEXT i
a1 = .0000305078125# * r
b1 = -5.972331524# - .99323946237# * r + .0000020767995# * r * r
IF r = 100 THEN b1 = -105.435
IF r = 200 THEN b1 = -203.06
IF r = 500 THEN b1 = -503.745
IF r = 1000 THEN b1 = -991.87
IF r = 2000 THEN b1 = -1983.74
IF r = 5000 THEN b1 = -4920.3
IF r = 10000 THEN b1 = -9762.5
LOCATE 10, 45: PRINT "Please wait....."
'OPEN dr$ + ":" + nam$ FOR OUTPUT AS #1
'PRINT #1, rd1$
'CLOSE #1
FOR i = 1 TO nseg
LOCATE 22, 5: PRINT "Segment #"; i; " * "; MID$(rd1$, (i - 1) * 4132 + 1, 55)
st = (i - 1) * 4132 + 33
FOR jj% = 1 TO 2048
jk% = (i - 1) * 2048 + jj%: temp$ = MID$(rd1$, st, 2)
aa = ASC(MID$(temp$, 1, 1)): ab = ASC(MID$(temp$, 2, 1)):
abc = aa + ab * 256: rd(jk%) = a1 * abc + b1: st = st + 2
NEXT jj%
NEXT i
n = 2048 * nseg
END SUB

SUB retenter (row, col) STATIC
strg$ = "Press ENTER to continue..."
IF col <> 0 THEN LOCATE row, col: PRINT SPACES(75 - col)
IF col = 0 THEN CALL censtr(row, strg$) ELSE LOCATE row, col: PRINT strg$
LSP1: IF INKEY$ <> CHR$(13) THEN GOTO LSP1
END SUB

SUB sd375 (x(), spectnp) STATIC
LINE (510, 135)-(990, 445), 0, BF: LOCATE 10, 45: PRINT "Please, wait ..."
bdname$ = "sd375": spectnp = 400
CALL ibfind(bdname$, bd%): CALL ibsic(bd%): v% = 1: CALL IBSRE(bd%, v%)
v% = 11: CALL ibtmo(bd%, v%)
v% = &H70 'get calibration data
CALL ibsad(bd%, v%): rd$ = SPACES(80): CALL ibrd(bd%, rd$)
fmin = VAL(MID$(rd$, 1, 7)): fmax = VAL(MID$(rd$, 8, 7))
uyb = VAL(MID$(rd$, 15, 5)): uyt = VAL(MID$(rd$, 20, 5))
lyb = VAL(MID$(rd$, 39, 5)): lyt = VAL(MID$(rd$, 44, 5))
' PRINT fmin, fmax, uyb, uyt, lyb, lyt
v% = &H6C 'Extract freq. spectrum or anything on the screen

```

```

CALL ibsad(bd$, v$)
rd$ = SPACES(401); CALL ibrd(bd$, rd$) 'get the data
LOCATE 21, 5: PRINT LEFT$(rd$, 55)
FOR i% = 2 TO 401 'convert the data
  kk% = i% - 1: temp = ASC(MID$(rd$, i%, 1))
  x(kk%) = uyb + (temp / 241) * (uyt - uyb)
  IF kk% < 15 THEN PRINT kk%, x(kk%)
NEXT i%
LOCATE 20, 15: PRINT "Please wait, Storing ..... " + SPACES(40)
Store the data on the disk
OPEN dr$ + ":\ " + nam$ + ".mag" FOR OUTPUT AS #1
WRITE #1, fmin, fmax, uyb, uyt, lyb, lyt
FOR i% = 1 TO 400
  WRITE #1, x(i%)
NEXT i%
CLOSE #1

END SUB

SUB statres (rd(), np) STATIC
DIM sdr(500), xx(500)
REDIM yy(500)
LINE (510, 135)-(990, 445), 0, BF
LOCATE 6, 45: PRINT "STATISTICAL ANALYSIS"
LOCATE 8, 45: INPUT "Amplitude range : "; rg
LOCATE 9, 45: INPUT "Number of class : "; divs
LOCATE 13, 45: PRINT "Please wait ....."
' statistical analysis
'--- set the boundary & mid-point x-values
inc = (2 * rg) / divs: sdr(1) = 0
FOR i = 2 TO divs + 1
  sdr(i) = sdr(i - 1) + inc: xx(i - 1) = (sdr(i) + sdr(i - 1)) / 2
NEXT i
'--- start the statistical analysis
sumrms = 0: FOR i = 1 TO 5: sum(i) = 0: NEXT i
FOR i = 1 TO np: sumrms = sumrms + rd(i) * rd(i): NEXT i
rmsrd = SQR(sumrms / np)
'--- grouping
FOR i = 1 TO divs: yy(i) = 0: NEXT i
crg = 0
FOR i = 1 TO np: xy = INT((rd(i) + rg) / inc)
  IF xy < 0 OR xy > divs THEN crg = crg + 1
  IF xy < 0 THEN xy = 1
  IF xy > divs THEN xy = divs
  yy(xy) = yy(xy) + 1: NEXT i

FOR i = 1 TO divs: sum(1) = sum(1) + yy(i): sum(2) = sum(2) + xx(i) * yy(i)
sum(3) = sum(3) + yy(i) * yy(i): NEXT i
IF crg <> 0 THEN LOCATE 13, 45: PRINT "Number of point out of range": crg
rmsfd = SQR(sum(3) / divs): mean = sum(2) / sum(1): sum(2) = 0: sum(3) = 0
FOR i = 1 TO divs
  dx = xx(i) - mean: FOR j = 2 TO 4: sum(j) = sum(j) + dx ^ j * yy(i): NEXT j
NEXT i
FOR i = 2 TO 4: sum(i) = sum(i) / sum(1): NEXT i
std = SQR(sum(2)): sk = sum(3) / std ^ 3: kur = sum(4) / std ^ 4
PRINT mean, std, sk, kur, rmsrd, rmsfd
END SUB

SUB stfft (x(), inv, n) STATIC
REDIM xr(n), xi(n)
FOR i% = 1 TO n: xr(i%) = x(i%): xi(i%) = 0: NEXT i%
DIM ur(20), ui(20)
ur(1) = 0: ui(1) = 1: FOR i% = 2 TO 15
  ur(i%) = SQR((1 + ur(i% - 1)) / 2): ui(i%) = ui(i% - 1) / (2 * ur(i%))
NEXT i%: n0 = 1: i1% = 0
i140: n0 = n0 + n0: i1% = i1% + 1: IF n0 < n THEN GOTO i140
  i1% = n0 / 2
  i3% = 1: i0% = i1%: FOR i4% = 1 TO i1%: FOR k% = 1 TO i1%
    wr = 1: w1 = 0: kk% = k% - 1: FOR i% = 1 TO i0%
      IF kk% = 0 THEN GOTO i240
      IF kk% MOD 2 = 0 THEN GOTO i230
      j0% = i0% - i%: ws = wr * ur(j0%) - w1 * ui(j0%)
      w1 = wr * ui(j0%) + w1 * ur(j0%): wr = ws
    i230: kk% = INT(kk% / 2) ' this stm is very important
  NEXT i%
  i240: IF inv = 0 THEN w1 = -w1
  i% = k%: FOR j% = 1 TO i3%

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11% = l% + i1%: zr = xr(l%) + xr(11%): zi = xi(l%) + xi(11%)
z = wr * (xr(l%) - xr(11%)) - wi * (xi(l%) - xi(11%))
xi(11%) = wr * (xi(l%) - xi(11%)) + wi * (xr(l%) - xr(11%))
xr(11%) = z: zr(l%) = zr: xi(l%) = zi: l% = 11% + i1%
NEXT j%: NEXT K%: i0% = i0% - 1: i3% = i3% + i3%: i1% = i1% / 2: NEXT i4%
um = 1!: IF inv = 0 THEN um = 1! / n0
FOR j% = 1 TO n0: K% = 0: j1% = j% - 1
FOR i% = 1 TO i1%: K% = 2 * K% + j1% MOD 2: j1% = INT(j1% / 2): NEXT i%
K% = K% + 1: IF K% < j% THEN GOTO i310
zr = xr(j%): zi = xi(j%): xr(j%) = xr(K%) * um: xi(j%) = xi(K%) * um
xr(K%) = zr * um: xi(K%) = zi * um
i310: NEXT j%
FOR i% = 1 TO n / 2 - 1: x(i%) = 2 * SQR(xr(i% + 1) ^ 2 + xi(i% + 1) ^ 2): NEXT i%
esub: END SUB

SUB windbox (px1, py1, px2, py2) STATIC
VIEW: WINDOW (0, 0)-(1000, 500)
pxr = px2 - px1 + 1: pyr = py2 - py1 + 1
REDIM gst1%(INT(pxr / 8 + 1) * pyr * CB% / 2 + 4)
GET (px1, py1)-(px2, py2), gst1%
LINE (px1, py1)-(px2, py2), 0, BF
LINE (px1, py1)-(px2, py2), , B
END SUB

```

```

:
:
:      <<<< CURVE FIT AND PLOTTING >>>>
:
DECLARE SUB ret13 (row, col)
DECLARE SUB windbox (px1, py1, px2, py2)
DECLARE SUB censtr (row, strg$)
DECLARE SUB plot (x(), y(), np)
DIM SHARED v(10), n, pg$, overlay$, cfflag$, SBOL$(10)
DIM SHARED ibsta$, iberr$, ibcnt$, ngraph, gcode$
DIM SHARED plotsp$, xs, ys, GT$, x1, y1, x2, y2
'DYNAMIC
DIM SHARED gst$(10), icc, sb$, CB$, gst1$(10), nolay$
DIM SHARED xmin, xmax, ymin, ymax, xdiv, ydiv, a, B
DIM a(10, 10), r(10), B(10), P(10), x(4100), y(4100), xy(4100, 2); FLD$(10)
LHK: CLS : ON ERROR GOTO errtrap1
  SBOL$(1) = "NE3 NF3 NG3 NH3": SBOL$(2) = "NU3 NL3 ND3 NR3"
  SBOL$(3) = "BH2 R4 D4 L4 U4 BF2": SBOL$(4) = "BNU0"
  CLS : LOCATE 1, 2: FOR i$ = 2 TO 79: PRINT " "; : NEXT i$
  FOR i = 2 TO 24: LOCATE i, 2: PRINT " "; : LOCATE i, 79: PRINT " "; : NEXT i
  LOCATE 25, 2: FOR i$ = 2 TO 79: PRINT " "; : NEXT i$
  strg$ = "<<< CURVE FIT AND PLOTTING >>>": CALL censtr(4, strg$)
  LOCATE 6, 2: FOR i$ = 2 TO 79: PRINT " "; : NEXT i$
  LOCATE 10, 28: PRINT "Graphic card selection ";
  LOCATE 11, 28: PRINT "-----";
  LOCATE 13, 28: PRINT "1. Hercules garphic card ?";
  LOCATE 14, 28: PRINT "2. Color graphic card (CGA)?" ;
  LOCATE 15, 28: PRINT "3. EGA ?";
  LOCATE 16, 28: PRINT "4. None ?"
  lsp3: LOCATE 18, 28: INPUT "Selection (1/2/3/4) :", gtsel$: gtsel = VAL(gtsel$)
  IF gtsel < 1 OR gtsel > 4 THEN GOTO lsp3
  IF gtsel = 4 THEN GOTO proc
  overlay$ = "0": ngraph = 0: nolay$ = 0: CB$ = 1
  IF gtsel = 1 THEN pg$ = 3
  IF gtsel = 2 THEN pg$ = 2
  IF gtsel = 3 THEN pg$ = 9: CB$ = 2
  SCREEN pg$
  ON ERROR GOTO 0
  restart:
  CLS : VIEW PRINT 1 TO 25
  cfflag$ = "0": GOSUB logo: CALL windbox(280, 330, 720, 410)
  LOCATE 7, 27: INPUT "Data on file (y/n) (Q)uit "; an$: an$ = UCASE$(an$)
  IF an$ = "Q" THEN GOTO proc
  IF NOT (an$ = "Y" OR an$ = "N") THEN GOTO restart
  IF an$ = "N" THEN GOTO edata
  GOSUB 2100
  IF aa$ = "Q" THEN GOTO restart
  GOSUB pfile
  GOSUB logo: LOCATE 14, 49: PRINT "Reading..": icol = 57
  OPEN dr$ + ":" + nam$ FOR INPUT AS #1
  IF pfset = 2 THEN
    INPUT #1, np, nc
    FOR i$ = 1 TO np: FOR j$ = 1 TO nc: INPUT #1, xy(i$, j$): NEXT j$
    ' IF i$ MOD 10 = 0 THEN icol = icol + 1: LOCATE 14, icol: PRINT "."
  NEXT i$
  ELSE
    LOCATE 17, 45: INPUT "Number of segment :", nseg
    FOR ii = 22 TO 24: LOCATE ii, 3: PRINT SPACES(75): NEXT ii
    FOR i$ = 1 TO nseg
      rd$ = INPUT$(4130, #1): GOSUB ExtFFot
      LOCATE 23, 7: PRINT "Segment #": i$: " "; LEFT$(rd$, 55)
      st = 33: ij$ = (i$ - 1) * 2048
      FOR j$ = 1 TO 2048
        temp$ = MID$(rd$, st, 2): aa = ASC(MID$(temp$, 1, 1))
        ab = ASC(MID$(temp$, 2, 1)): abc = (aa + ab * 256) - 32768
        xy(j$ + ij$, 1) = (FFot(1) * abc + FFot(2)) * 1000 'unit in [mV]
        st = st + 2
        ' IF j$ < 10 THEN PRINT j$, xy(j$ + ij$, 1)
      NEXT j$
    NEXT i$
    np = nseg * 2048: nc = 1
  END IF
  CLOSE #1: LOCATE 14, 49: PRINT SPACES(30);
  GOTO menu

edata:
LINE (20, 5)-(980, 445), 0, BF
strg$ = "Enter value '999' on a row to end input": CALL censtr(24, strg$)

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1k1: LOCATE 5, 28: INPUT "Number of column :", nc: IF nc > 7 THEN GOTO 1k1
jk = 10: FOR jj% = 1 TO nc: LOCATE 7, jk * jj% + 1: PRINT "Col.#": jj%: : NEXT jj%
VIEW PRINT 8 TO 22: j = 1
lsp4: ii = (j - 1) MOD 14 + 8
LOCATE ii, 2: PRINT SPACES(77): : LOCATE ii, 2: PRINT "Row ": j: "=":
ij = 10: FOR jj% = 1 TO nc: LOCATE ii, jj% * ij: INPUT "": xy(j, jj%): NEXT jj%
IF xy(j, 1) = 999 AND xy(j, 2) = 999 THEN GOTO lsp5
j = j + 1: GOTO lsp4
lsp5: np = j - 1
VIEW PRINT 1 TO 25
IF np = 0 THEN
LOCATE 24, 2: PRINT SPACES(77): strg$ = "No data entered.. .Press 'ENTER' to continue ..": CALL
censtr(24, strg$)
lp5: IF INKEY$ <> CHR$(13) THEN GOTO lp5
LINE (510, 5)-(990, 200), 0, BF: GOTO rstart
END IF

menu: CLS
VIEW PRINT 1 TO 25: GOSUB logo
LOCATE 6, 15: PRINT "Main menu": LOCATE 7, 13: PRINT "=====
LOCATE 10, 7: PRINT "1. plotting ?"
LOCATE 11, 7: PRINT "2. curve-fit ?"
LOCATE 12, 7: PRINT "3. data manipulation ?"
LOCATE 13, 7: PRINT "4. print to printer ?"
LOCATE 14, 7: PRINT "5. view port ?"
LOCATE 15, 7: PRINT "6. restart ?"
LOCATE 16, 7: PRINT "7. quit ?"
rent: LOCATE 18, 7: INPUT "selection (1-7) : ", sel$: sel = VAL(sel$)
IF sel < 1 OR sel > 7 THEN GOTO rent
IF sel = 7 THEN GOTO proc
IF sel = 6 THEN GOTO rstart
IF sel = 4 THEN GOSUB pprinter
IF sel = 2 THEN GOSUB xyaxis: GOSUB 1000
IF sel = 3 THEN GOSUB dataman
IF sel = 5 THEN
IF ngraph = 0 THEN
CALL windbox(20, 20, 980, 140)
strg$ = "No plots available, Go back and pick Plotting": CALL censtr(21, strg$)
strg$ = "Press 'ENTER' to go back ..": CALL censtr(23, strg$)
1kp3: IF INKEY$ <> CHR$(13) THEN GOTO 1kp3
LINE (20, 20)-(980, 140), 0, BF: PUT (20, 20), gst1$
ELSE
GOSUB ingput
END IF
END IF
IF sel = 1 THEN
LINE (10, 5)-(490, 445), 0, BF
LOCATE 6, 8: PRINT "Plotting": LOCATE 7, 5: PRINT "=====
LOCATE 9, 5: PRINT "(S)creen ?": LOCATE 10, 5: PRINT "(P)lotter ?"
p11: LOCATE 12, 5: INPUT "Choice (S/P) : ", plotsp$
plotsp$ = UCASE$(plotsp$)
IF plotsp$ = "Q" THEN GOTO menu
IF NOT (plotsp$ = "S" OR plotsp$ = "P") THEN GOTO p11
LOCATE 14, 5: PRINT "0. overlay plot ?"
LOCATE 15, 5: PRINT "1. single plot ?"
ls4: LOCATE 17, 5: INPUT "selection (0/1) : ", gcode$
IF NOT (gcode$ = "0" OR gcode$ = "1") THEN GOTO ls4
IF gcode$ = "0" AND overlay$ = "0" THEN
VIEW: WINDOW (0, 0)-(1000, 500): CALL windbox(20, 20, 980, 140)
strg$ = "You can not overlay plots - none available, Go back and pick option (1)": CALL
censtr(21, strg$)
strg$ = "Press 'ENTER' to go back ..": CALL censtr(23, strg$)
lp3: IF INKEY$ <> CHR$(13) THEN GOTO lp3
LINE (20, 20)-(980, 140), 0, BF: PUT (20, 20), gst1$
GOTO ls4
END IF
GOSUB xyaxis
IF gcode$ = "1" THEN
x7 = 1E+07: x8 = -1E+07: y7 = 1E+07: y8 = -1E+07
FOR i% = 1 TO np: GOSUB minmax: NEXT i%
LINE (510, 5)-(990, 445), 0, BF: LOCATE 5, 45: PRINT "Input plotting data : "
LOCATE 7, 45: PRINT "Xmin, Xmax =": TAB(59): USING "####.###": x7: TAB(70): x8
LOCATE 8, 45: PRINT "Ymin, Ymax =": TAB(59): USING "####.###": y7: TAB(70): y8
lsp9: LOCATE 9, 45: INPUT "Xmin, Xmax =", xmin, xmax
LOCATE 10, 45: INPUT "Ymin, Ymax =", ymin, ymax
IF plotsp$ = "P" THEN LOCATE 11, 45: INPUT "Xsep, Ysep =": xs, ys
p12: LOCATE 13, 45: INPUT "Satisfy (y/n) ?", an$: an$ = UCASE$(an$)
IF an$ = "Q" THEN GOTO menu

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IF NOT (an$ = 'Y' OR an$ = 'N') THEN GOTO pl2
IF an$ = 'N' THEN GOTO lsp9
factx = 1: facty = 1
IF xmax < 1 THEN factx = 10
IF xmax < .1 THEN factx = 100
IF ymax < 1 THEN facty = 10
IF ymax < .1 THEN facty = 100
FOR i% = 1 TO np: x(i%) = x(i%) * factx: y(i%) = y(i%) * facty: NEXT i%
xs = xs * factx: ys = ys * facty
xmin = xmin * factx: xmax = xmax * factx
ymin = ymin * facty: ymax = ymax * facty
END IF
LOCATE 15, 45: INPUT "symbol (1,2,3,4,5) :", sb%
IF plotsp$ = "S" THEN CALL plot(x(), y(), np)
IF plotsp$ = "P" THEN GOSUB PLOTTER
END IF
GOTO menu

errtrap1: LOCATE 21, 5: PRINT "**** ERROR - Unmatched graphic driver"
CALL ret13(23, 0): RESUME LHK

proc: CLS : END

ExtFFot: 'extract factor, offset, time scale, & time index
FFot$(1) = MID$(rd$, 1, 8): FFot$(2) = MID$(rd$, 9, 8)
FFot$(3) = MID$(rd$, 17, 8): FFot$(4) = MID$(rd$, 25, 8)
FOR fj% = 1 TO 3
  FOR fi% = 1 TO 8
    tempww = ASC(MID$(FFot$(fj%), fi%, 1))
    IF tempww < 58 THEN tempww = tempww - 48
    IF tempww > 64 THEN tempww = tempww - 55
    ww(fi%) = tempww
  NEXT fi%
  w1 = 2 ^ (ww(1) * 16 + ww(2) - 128)
  ww$ = ""
  FOR fi% = 3 TO 8
    GOSUB decbin
    ww$ = ww$ + binstr$
  NEXT fi%
  FOR fi% = 1 TO 24
    IF fi% = 1 THEN
      w234 = 2 ^ -1
    ELSE
      w234 = w234 + VAL(MID$(ww$, fi%, 1)) * 2 ^ (-ji%)
    END IF
  NEXT fi%
  FFot(fj%) = w1 * w234
NEXT fj%
RETURN

decbin:
IF ww(fi%) = 0 THEN binstr$ = "0000"
IF ww(fi%) = 1 THEN binstr$ = "0001"
IF ww(fi%) = 2 THEN binstr$ = "0010"
IF ww(fi%) = 3 THEN binstr$ = "0011"
IF ww(fi%) = 4 THEN binstr$ = "0100"
IF ww(fi%) = 5 THEN binstr$ = "0101"
IF ww(fi%) = 6 THEN binstr$ = "0110"
IF ww(fi%) = 7 THEN binstr$ = "0111"
IF ww(fi%) = 8 THEN binstr$ = "1110"
IF ww(fi%) = 9 THEN binstr$ = "1111"
RETURN

PLOTTER:
CLS : IF gcode$ = "0" THEN GOTO 1200
LOCATE 2, 15: PRINT "Graph type :"
1040 LOCATE 3, 17: PRINT "1). Vertical ?": LOCATE 4, 17: PRINT "2). Horizontal ?"
LOCATE 5, 15: INPUT "*** Selection (1/2) :", GT$
IF NOT (GT$ = "1" OR GT$ = "2") THEN 1040
LOCATE 7, 15: PRINT "X label :", LB$
LOCATE 8, 15: PRINT "Y label :", LL$
LOCATE 9, 15: PRINT "Title :", LT$
1140 LOCATE 11, 15: INPUT "Satisfy (y/n) :", an$: an$ = UCASE$(an$)
IF NOT (an$ = "Y" OR an$ = "N") THEN 1140
IF an$ = "Y" THEN 1160
LOCATE 7, 15: INPUT "X label :", LB$
LOCATE 8, 15: INPUT "Y label :", LL$

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LOCATE 9, 15: INPUT "Title :", LT$
GOTO 1140
1160 CX = LEN(LB$) / 2: CY = LEN(LL$) / 2
IF GT$ = "1" THEN
1165 LOCATE 11, 15: INPUT "p1 (x,y) :", x1, y1
LOCATE 12, 15: INPUT "p2 (x,y) :", x2, y2
1172 LOCATE 14, 15: INPUT "Satisfy (y/n) "; an$: an$ = UCASE$(an$)
IF NOT (an$ = "Y" OR an$ = "N") THEN 1172
IF an$ = "N" THEN 1165
END IF
1200 'Real plotting routine start here
PARAM$ = "INIT/1/&H330/P/": GOSUB 10000
LOCATE 16, 20: PRINT "wait.....": wrt$ = ""
IF GT$ = "1" THEN
wrt$ = wrt$ + "ro90;ip;iw;sp1;ip" + STR$(x1) + "," + STR$(y1) + "," + STR$(x2) + "," + STR$(y2)
END IF
IF GT$ = "2" THEN wrt$ = wrt$ + "ro;in;sp1;ip2300,2000,8000,6100"
wrt$ = wrt$ + "sc" + STR$(xmin) + "," + STR$(xmax) + "," + STR$(ymin) + "," + STR$(ymax)
wrt$ = wrt$ + "s10.2,0.28;t11.5,0;"
wrt$ = wrt$ + "pu" + STR$(xmin) + "," + STR$(ymin) + ";pd" + STR$(xmax) + "," + STR$(ymin) + ","
wrt$ = wrt$ + STR$(xmax) + "," + STR$(ymax) + "," + STR$(xmin) + ","
wrt$ = wrt$ + STR$(ymax) + "," + STR$(xmin) + "," + STR$(ymin) + "pu;"
IF gcode$ = "0" THEN GOTO iplot
FOR i = xmin TO xmax STEP xs
wrt$ = wrt$ + "pa" + STR$(i) + "," + STR$(ymin) + ";xt"
dx = (LEN(STR$(i)) - 1) / 2: xx$ = STR$(i / factx)
wrt$ = wrt$ + "cp" + STR$(-dx) + ",-1.2;lb" + xx$ + CHR$(3)
NEXT i
FOR y = ymin TO ymax STEP ys
wrt$ = wrt$ + "pa" + STR$(xmin) + "," + STR$(y) + ";yt": yy$ = STR$(y / facty)
IF y < 0 AND ABS(y) > 9999 THEN wrt$ = wrt$ + "cp-7,-0.25;lb" + yy$ + CHR$(3): GOTO 114
IF y < 0 AND ABS(y) > 999 THEN wrt$ = wrt$ + "cp-6,-0.25;lb" + yy$ + CHR$(3): GOTO 114
IF y > 0 AND ABS(y) > 999 THEN wrt$ = wrt$ + "cp-6,-0.25;lb" + yy$ + CHR$(3): GOTO 114
IF ABS(y) < 100 THEN wrt$ = wrt$ + "cp-4,-0.25;lb" + yy$ + CHR$(3): GOTO 114
IF ABS(y) > 99 THEN wrt$ = wrt$ + "cp-5,-0.25;lb" + yy$ + CHR$(3)
114: NEXT y
GOSUB WRSTR: wrt$ = ""
wrt$ = wrt$ + "pa" + STR$(xmin) + "," + STR$((ymin + ymax) / 2) + "s10.2,0.3;di0,1;cp" + STR$(-CY)
+ ",3"
wrt$ = wrt$ + "lb" + LL$ + CHR$(3): CX = LEN(LB$) / 2
wrt$ = wrt$ + "di;pa" + STR$((xmin + xmax) / 2) + "," + STR$(ymin) + "s10.2,0.3;cp" + STR$(-CX) +
",-2.5"
wrt$ = wrt$ + "lb" + LB$ + CHR$(3): CX = LEN(LT$) / 2
wrt$ = wrt$ + "pa" + STR$((xmin + xmax) / 2) + "," + STR$(ymax) + "cp" + STR$(-CX) + ",2"
wrt$ = wrt$ + "lb" + LT$ + CHR$(3)
GOSUB WRSTR: wrt$ = ""
iplot: ' plotting
FOR i% = 1 TO np
IF (x(i%) < xmin) OR x(i%) >= xmax THEN GOTO i31
IF (y(i%) <= ymin) OR y(i%) >= ymax THEN GOTO i31
wrt$ = "pa" + STR$(x(i%)) + "," + STR$(y(i%))
IF sb% < 5 THEN GOSUB subasy
IF sb% = 5 THEN wrt$ = wrt$ + "pd"
GOSUB WRSTR
i31: NEXT i%
overlay$ = "1"
ip1: LOCATE 16, 11: INPUT "Press (F) to overlay best fit curve or (C) to continue.. ", aa$
aa$ = UCASE$(aa$)
IF NOT (aa$ = "F" OR aa$ = "C") THEN GOTO ip1
IF aa$ = "F" THEN
IF cfflag$ = "0" THEN
CALL windbox(100, 100, 900, 200)
strg$ = "No best fit curves available, Go back and Run 'Curve-fit': CALL censtr(17, strg$)
strg$ = "Press 'ENTER' to go back ..": CALL censtr(18, strg$)
is5: IF INKEY$ <> CHR$(13) THEN GOTO is5
LINE (100, 100)-(900, 200), 0, BF: PUT (100, 100), gst1%
ELSE
i1% = 1
OPEN "A:TEMPDUMP" FOR OUTPUT AS #3
sep = ABS((xmin - xmax) / 100): i = xmin
is7: IF icc = 2 AND i = 0 THEN i = i + sep
IF i >= xmax THEN GOTO is6
ON icc GOTO is8, is9, is10, is11, is12
is8: sum = a + B * i: GOTO ippt
is9: sum = a + B * LOG(i): GOTO ippt
is10: sum = a + i ^ B: GOTO ippt
is11: sum = a * EXP(B * i): GOTO ippt
is12: sum = 0

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        FOR j% = 1 TO n: sum = sum + v(j%) * i ^ (j% - 1): NEXT j%
ippt: IF sum <= ymin OR sum >= ymax THEN GOTO iik
PRINT #3, USING "####.##"; i; : PRINT #3, "; "; USING "####.##"; sum
iik = iik + 1
iik: i = i + sep: GOTO is7
is6: CLOSE #3          'finish curve fit
wrt$ = "sp2": GOSUB WRSTR
OPEN "A:TEMPODUMP" FOR INPUT AS #3
FOR i% = 1 TO iik - 1
INPUT #3, ixx, iyy
wrt$ = "pa" + STR$(ixx) + ", " + STR$(iyy) + "1b." + CHR$(3)
GOSUB WRSTR
NEXT i%
CLOSE #3
        END IF
END IF
wrt$ = "SP0:IN:IP": GOSUB WRSTR
RETURN

subsym:
ON sb% GOTO 122, 124, 126, 128, 130
122: wrt$ = wrt$ + "uc-3,-2,99,6,0,-3,4,-3,-4;": GOTO 130
124: wrt$ = wrt$ + "uc-2,-2,99,4,0,0,4,-4,0,0,-4;": GOTO 130
126: wrt$ = wrt$ + "uc0,-3,99,0,6,-99,-3,-3,99,6,0;": GOTO 130
128: wrt$ = wrt$ + "uc0,-3,99,3,3,-3,3,-3,-3,3,-3;": GOTO 130
130: RETURN

WRSTR: DATA.STRING$ = wrt$: PARAM$ = "WR.STR/4//EOS/": GOSUB 10000: RETURN

xyaxis:
IF nc = 2 THEN
FOR i% = 1 TO np: x(i%) = xy(i%, 1): y(i%) = xy(i%, 2): NEXT i%
ELSEIF nc = 1 THEN
FOR i% = 1 TO np: x(i%) = i%: y(i%) = xy(i%, 1): NEXT i%
ELSE
CALL windbox(200, 50, 800, 200)
lc1: LOCATE 17, 30: INPUT "X-axis: column# : ", xx
LOCATE 19, 30: INPUT "Y-axis: column# : ", yy
strg$ = "Press (R)eenter or (C) to continue..": CALL censtr(21, strg$)
lc2: INPUT " ", an$
IF NOT (an$ = "R" OR an$ = "r" OR an$ = "C" OR an$ = "c") THEN GOTO lc2
IF an$ = "R" OR an$ = "r" THEN GOTO lc1
LINE (200, 50)-(800, 200), 0, BF: PUT (200, 50), gst1%
FOR i% = 1 TO np
x(i%) = xy(i%, xx): y(i%) = xy(i%, yy)
NEXT i%
END IF
RETURN

1000 ' curve-fit
lsp10: LINE (10, 5)-(490, 445), 0, BF
LOCATE 6, 6: PRINT "Least Square Curve Fit": LOCATE 7, 5: PRINT "=====
LOCATE 10, 5: PRINT "1. Linear :Y=a+b*X ?"
LOCATE 11, 5: PRINT "2. Logarithmic :Y=a+b*LOG(X) ?"
LOCATE 12, 5: PRINT "3. Power :Y=a*X^b ?"
LOCATE 13, 5: PRINT "4. Exponential :Y=a*EXP(b*X) ?"
LOCATE 14, 5: PRINT "5. Polynomial Curve fit ?"
LOCATE 15, 5: PRINT "6. Return ?"
LSP11: LOCATE 17, 5: INPUT "Selection (1-6) : "; ic$: ic = VAL(ic$)
IF ic = 6 THEN RETURN
IF ic < 1 OR ic > 6 THEN GOTO LSP11
icc = ic
IF ic = 5 THEN GOSUB 1400: GOTO lsp10
GOSUB 2400: GOTO lsp10
RETURN

1400 REM: Polynomial curve-fit
1420 md = 7: ef = 999
LINE (510, 5)-(990, 445), 0, BF: LOCATE 5, 45: PRINT "Polynomial curve fit";
1430 LOCATE 24, 45: PRINT SPACES(34); : LOCATE 6, 45: INPUT "Degree of polynomial : "; d:
1440 IF d < 0 THEN LOCATE 24, 45: PRINT "Degree must be >=0"; : GOTO 1430
1450 d = INT(d): IF d < np THEN 1470
1460 LOCATE 24, 45: PRINT "Not enough data"; : GOTO 1430
1470 d2 = 2 * d: IF d > md THEN LOCATE 24, 45: PRINT "Degree too high"; : GOTO 1430
1480 n = d + 1: FOR j = 1 TO d2: P(j) = 0: FOR k = 1 TO np
1500 P(j) = P(j) + x(k) ^ j: NEXT: NEXT: P(0) = np
1510 r(1) = 0: FOR j = 1 TO np: r(1) = r(1) + y(j)
1520 NEXT: IF n = 1 THEN 1550

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1530 FOR j = 2 TO n: r(j) = 0: FOR k = 1 TO np
1540 r(j) = r(j) + y(k) * x(k) ^ (j - 1): NEXT: NEXT
1550 FOR j = 1 TO n: FOR k = 1 TO n: a(j, k) = P(j + k - 2): NEXT: NEXT
1560 GOSUB 1820
1570 LOCATE 7, 45: PRINT "x power          coefficient"
1600 FOR j = 1 TO n: LOCATE 7 + j, 45: PRINT " "; j - 1; TAB(62); USING "####.####"; v(j): NEXT
1610 q = 0: FOR j = 1 TO np: q = q + y(j): NEXT: M = q / np: t = 0: g = 0: FOR j = 1 TO np
1620 q = 0: FOR k = 1 TO n: q = q + v(k) * x(j) ^ (k - 1): NEXT: t = t + (y(j) - q) ^ 2
1630 g = g + (y(j) - M) ^ 2: NEXT: IF g = 0 THEN rr = 1: GOTO 1650
1640 rr = SQR(1 - t / g)
1645 cflag$ = "1"
1650 LOCATE 16, 45: PRINT "Correlation Coeff. [r] = "; USING "####.####"; rr
1670 LOCATE 17, 45: PRINT "1 - Fit a specific point"
1685 LOCATE 18, 45: PRINT "2 - Fit another degree to data"
1690 LOCATE 19, 45: PRINT "3 - Continue"
1700 LOCATE 20, 45: INPUT "what next?"; q
1705 q = INT(q): IF q = 3 THEN 2000
1710 IF q = 2 THEN 1420
1720 IF q <> 1 THEN 1700
1730 LOCATE 22, 45: PRINT "enter "; ef; " to leave this mode";
1740 LOCATE 23, 45: INPUT "x="; xv: IF xv = ef THEN 1700
1750 yv = 0: FOR k = 1 TO n: yv = yv + v(k) * xv ^ (k - 1): NEXT
1760 LOCATE 24, 45: PRINT "X,y="; xv, yv;
1770 GOTO 1740
1820 IF n = 1 THEN v(1) = r(1) / a(1, 1): RETURN
1830 FOR k = 1 TO n - 1: i = k + 1: l = k
1840 IF ABS(a(i, k)) > ABS(a(l, k)) THEN l = i
1870 IF l < n THEN l = l + 1: GOTO 1860
1880 IF l = k THEN 1720
1890 FOR j = k TO n: q = a(k, j): a(k, j) = a(l, j): a(l, j) = q: NEXT
1910 q = r(k): r(k) = r(l): r(l) = q
1920 i = k + 1
1930 q = a(i, k) / a(k, k): a(i, k) = 0
1940 FOR j = k + 1 TO n: a(i, j) = a(i, j) - q * a(k, j): NEXT
1950 r(i) = r(i) - q * r(k): IF i < n THEN i = i + 1: GOTO 1930
1960 NEXT
1970 v(n) = r(n) / a(n, n): FOR i = n - 1 TO 1 STEP -1: q = 0: FOR j = i + 1 TO n
1990 q = q + a(i, j) * v(j): v(i) = (r(i) - q) / a(i, i): NEXT: NEXT
2000 RETURN

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logo:

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SCREEN pg$: WINDOW (0, 0)-(1000, 500): LINE (0, 0)-(1000, 500), 0, BF
LINE (0, 0)-(1000, 500), , B
strg$ = "Curve fit & plotting routine": CALL censtr(2, strg$)
LINE (0, 450)-(1000, 450)
LINE (500, 0)-(500, 450): LOCATE 2, 72: PRINT "V3.0 HK"
RETURN

```

```

2100 REM: file handling
CALL windbox(200, 100, 800, 200)
lsp7: LOCATE 17, 19: INPUT "Filename : "; nam$
LOCATE 18, 19: INPUT "Drive (a/b/c or path) :"; dr$
lsp6: LOCATE 19, 19: INPUT "Satisfy (y/n) ?"; aa$: aa$ = UCASE$(aa$)
IF aa$ = "Q" THEN RETURN
IF NOT (aa$ = "Y" OR aa$ = "N") THEN GOTO lsp6
IF aa$ = "N" THEN GOTO lsp7
LINE (200, 100)-(800, 200), 0, BF: PUT (200, 100), gst1$
RETURN

```

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pfile: 'pick the type of data file
CALL windbox(200, 100, 800, 200)
LOCATE 17, 22: PRINT "1. Raw data [Binary from PROWLER] ?"
LOCATE 18, 22: PRINT "2. General data ?"
pf11: LOCATE 19, 22: INPUT "Selection (1/2) :"; pfsel
IF pfsel < 1 OR pfsel > 2 THEN GOTO pf11
LINE (200, 100)-(800, 200), 0, BF: PUT (200, 100), gst1$
RETURN

```

```

2300 REM: View data
LINE (20, 5)-(980, 445), 0, BF: LOCATE 5, 10: PRINT "Number of row :"; np
LOCATE 5, 50: PRINT "Number of column :"; nc: LOCATE 7, 5: PRINT "##"
jk = 10: FOR jj% = 1 TO nc: LOCATE 7, jj% * jk + 1: PRINT "Col.##"; jj%; : NEXT jj%
VIEW PRINT 8 TO 23
FOR i% = 1 TO np
IF INKEY$ = CHR$(32) THEN GOTO outpl
ii = (i% - 1) MOD 15 + 8: LOCATE ii, 2: PRINT SPACES(77): LOCATE ii, 5: PRINT i%
FOR jj% = 1 TO nc: LOCATE ii, jj% * jk + 1: PRINT USING "####.####"; xy(i%, jj%): NEXT jj%
NEXT i%

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outpl: VIEW PRINT 1 TO 25
strg$ = 'Press 'ENTER' to continue ...'; CALL censtr(24, strg$)
lk2: IF INKEY$ <> CHR$(13) THEN GOTO lk2
GOSUB logo
RETURN

```

```

pprinter: LINE (510, 5)-(990, 445), 0, BF
LOCATE 5, 45: PRINT "Print Data to printer": LOCATE 6, 45: PRINT "=====
LOCATE 10, 45: PRINT "Make sure printer is ON": LOCATE 12, 45: PRINT "Press (P) to print ..."
LOCATE 13, 45: PRINT "Press (Q) to exit printing.."
lk3: a$ = INKEY$: IF NOT (UCASE$(a$) = "P" OR UCASE$(a$) = "Q") THEN GOTO lk3
IF UCASE$(a$) = "Q" THEN RETURN
LOCATE 15, 50: PRINT "Wait ..printing"
LPRINT TAB(10); "Number of row :"; np; : LPRINT TAB(50); "Number of column :"; nc
LPRINT : LPRINT
LOCATE , 5: LPRINT "#";
'jk = 10: FOR jj% = 1 TO nc: LOCATE , jj% * jk + 1: LPRINT "Col.#"; jj%; : NEXT jj%
FOR i% = 1 TO np: LPRINT TAB(5); i%;
FOR jj% = 1 TO nc: LOCATE , jj% * jk + 1: LPRINT USING "###.###"; xy(i%, jj%); : NEXT jj%
NEXT i%
LPRINT : LOCATE 15, 50: PRINT "Printing .....done"
RETURN

```

```

2399 REM          curve-fitssss
2400 x0 = 0: y0 = 0: x2 = 0: y2 = 0: x3 = 0
2410 FOR i% = 1 TO np
2420 ON ic GOTO 2430, 2440, 2450, 2460
2430 c = x(i%): d = y(i%): GOTO 2470
2440 c = LOG(x(i%)): d = y(i%): GOTO 2470
2450 c = LOG(x(i%)): d = LOG(y(i%)): GOTO 2470
2460 c = x(i%): d = LOG(y(i%))
2470 x0 = x0 + c: y0 = y0 + d
2480 x2 = x2 + c * c: x3 = x3 + c * d: y2 = y2 + d * d
2490 NEXT i%
2500 x0 = x0 / np: y0 = y0 / np
2510 B = (x3 - np * x0 * x0) / (x2 - np * x0 * x0): a = y0 - B * x0
2530 IF ic < 3 THEN 2550
2540 a = EXP(a)
2550 r2 = B * B * (x2 - np * x0 * x0) / (y2 - np * y0 * y0)
2555 rr = SQR(r2): s = 0
2570 FOR i% = 1 TO np
2580 ON ic GOTO 2590, 2600, 2610, 2620
2590 s0 = a + B * x(i%) - y(i%): GOTO 2630
2600 s0 = a + B * LOG(x(i%)) - y(i%): GOTO 2630
2610 s0 = a * (x(i%) ^ B) - y(i%): GOTO 2630
2620 s0 = a * EXP(B * x(i%)) - y(i%)
2630 s = s + s0 * s0
2640 NEXT i%
LINE (510, 5)-(990, 445), 0, BF
ON ic GOTO 11, 12, 13, 14
11: LOCATE 5, 45: PRINT "Linear :Y=a+b*X ": GOTO 15
12: LOCATE 5, 45: PRINT "Logaritmhc :Y=a+b*LOG(X) ": GOTO 15
13: LOCATE 5, 45: PRINT "Power :Y=a*X^b ": GOTO 15
14: LOCATE 5, 45: PRINT "Exponential :Y=a*EXP(b*X) "
15: cfflag$ = "1"
2650 LOCATE 7, 45: PRINT "a :"; USING "###.###"; a
2655 LOCATE 8, 45: PRINT "b :"; USING "###.###"; B
2660 LOCATE 9, 45: PRINT "Correlation coeff. [r] = "; USING "###.###"; rr
2670 LOCATE 10, 45: PRINT "square of residuals :"; USING "###.###"; s
2680 LOCATE 12, 45: PRINT "1. Fit a specific point ?"
2690 LOCATE 13, 45: PRINT "2. Continue ?"
2710 LOCATE 15, 45: INPUT "Selection (1-2) : ", zz$: zz = VAL(zz$)
2720 IF zz < 1 OR zz > 2 THEN 2680
2730 IF zz = 2 THEN 2900
2750 LOCATE 16, 45: INPUT "x = "; x1
2760 ON ic GOTO 2770, 2780, 2790, 2800
2770 y1 = a + B * x1: GOTO 2810
2780 y1 = a + B * LOG(x1): GOTO 2810
2790 y1 = a * x1 ^ B: GOTO 2810
2800 y1 = a * EXP(B * x1)
2810 LOCATE 17, 45: PRINT "*** x,y ="; x1; " , "; y1
2820 GOTO 2680
2900 RETURN

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dataman:
' data manipulation
LINE (10, 5)-(490, 445), 0, BF
LOCATE 6, 10: PRINT "Data Manipulation": LOCATE 7, 8: PRINT "=====

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LOCATE 10, 10: PRINT "1. adding data ?"
LOCATE 11, 10: PRINT "2. changing data ?"
LOCATE 12, 10: PRINT "3. deleting data ?"
LOCATE 13, 10: PRINT "4. view data ?"
LOCATE 14, 10: PRINT "5. save data ?"
LOCATE 15, 10: PRINT "6. Return ?"
LSP1: LOCATE 17, 10: INPUT "selection (1-6) :", zz$: zz = VAL(zz$)
IF zz < 1 OR zz > 6 THEN GOTO LSP1
IF zz = 6 THEN RETURN
IF zz = 1 THEN GOSUB adata
IF zz = 2 THEN GOSUB cdata
IF zz = 3 THEN GOSUB ddata
IF zz = 4 THEN GOSUB 2300
IF zz = 5 THEN GOSUB sdata
GOTO dataman

minmax:
IF y(i%) > y8 THEN y8 = y(i%)
IF y(i%) < y7 THEN y7 = y(i%)
IF x(i%) > x8 THEN x8 = x(i%)
IF x(i%) < x7 THEN x7 = x(i%)
RETURN

sdata:
GOSUB 2100: IF aa$ = "2" OR aa$ = "q" THEN RETURN
LINE (510, 5)-(990, 445), 0, BF: LOCATE 5, 45: PRINT "Saving :"; dr$ + nam$
LOCATE 14, 49: PRINT "Wait, Saving ": icol = 61
OPEN dr$ + nam$ FOR OUTPUT AS #1
PRINT #1, np, nc
FOR i% = 1 TO np
FOR j% = 1 TO nc - 1: PRINT #1, xy(i%, j%); ", "; : NEXT j%: PRINT #1, xy(i%, nc)
IF i% MOD 10 = 0 THEN icol = icol + 1: LOCATE 14, icol: PRINT ". "
NEXT i%
CLOSE #1: LOCATE 14, 49: PRINT "Finish saving.."; nam$
RETURN

cdata:
LINE (510, 5)-(990, 445), 0, BF: LOCATE 5, 45: PRINT "Changing data "
LOCATE 7, 45: INPUT "which point ?", ii
LOCATE 9, 45: PRINT "X 1 -"; TAB(51); xy(ii, 1)
FOR j% = 2 TO nc: LOCATE , 45: PRINT "X"; j%; " = "; TAB(51); xy(ii, j%): NEXT j%
LOCATE CSRLIN + 2, 45: INPUT "This set of values (y/n) ?", an$
IF NOT (an$ = "y" OR an$ = "Y") THEN RETURN
LINE (550, 5)-(990, 350), 0, BF
LOCATE 9, 45: PRINT "Enter new data values : "
LOCATE 10, 45: PRINT "X 1 = "; : INPUT "", xy(ii, 1)
FOR j% = 2 TO nc: LOCATE , 45: PRINT "X"; j%; : INPUT " = ", xy(ii, j%): NEXT j%
RETURN

adata:
LINE (510, 5)-(990, 445), 0, BF: LOCATE 5, 45: PRINT "Add data "
LOCATE 7, 45: INPUT "which point :", st: LOCATE 8, 45: PRINT "Wait...."
FOR i% = np TO st STEP -1
FOR j% = 1 TO nc: xy(i% + 1, j%) = xy(i%, j%): NEXT j%
NEXT i%
LOCATE 8, 45: PRINT SPACES(20): LOCATE 9, 45: PRINT "Enter new values : "
FOR j = 1 TO nc
LOCATE , 45: PRINT "x"; j; : INPUT " = ", xy(st, j)
NEXT j
np = np + 1
RETURN

ddata:
LINE (510, 5)-(990, 445), 0, BF: LOCATE 5, 45: PRINT "Delete data "
lsp2: LOCATE 9, 45: PRINT SPACES(34): LOCATE 7, 45: INPUT "which point :", st
IF st < 1 OR st > np THEN LOCATE 9, 45: PRINT "out of range - try again": GOTO lsp2
LOCATE 9, 45: PRINT "Current data values are : "
FOR j% = 1 TO nc: LOCATE , 51: PRINT "X"; j%; " = "; xy(st, j%): NEXT j%
LOCATE , 45: INPUT "Are you sure (y/n) ?", an$
IF NOT (an$ = "Y" OR an$ = "y") THEN RETURN
LOCATE , 49: PRINT "Wait ...."
FOR i% = st TO np - 1
FOR j% = 1 TO nc: xy(i%, j%) = xy(i% + 1, j%): NEXT j%
NEXT i%
np = np - 1
RETURN

imgput:

```

```

SCREEN pg%: CLS : VIEW: WINDOW
IF pg% = 2 THEN PUT (30, 5), gsc%
IF pg% = 9 THEN PUT (30, 50), gsc%
IF pg% = 3 THEN PUT (10, 5), gsc%
la3: IF INKEY$ <> CHR$(13) THEN GOTO la3
CLS
RETURN

```

```

9960 REM ***** START OF << IEEE-488 >> SUBROUTINE *****
10000 GOSUB 21560 'FETCH COMMAND
10160 IF FLDS(0) = "INIT" GOTO 11800
10400 IF FLDS(0) = "RD.STR" GOTO 14060
10440 IF FLDS(0) = "RD.TO.FILE" GOTO 14780
10740 IF FLDS(0) = "WR.STR" GOTO 15280
10820 PRINT "Undefined command...execution terminated"
10840 PRINT PARAM$
10860 END
11760 REM ***** INIT *****
11780 REM
11800 IEEE.FCTN$ = "INIT - INITIALIZATION "
11820 TRUE% = &HFF: FALSE% = 0
11840 REDIM REC$(30)
11860 MY.FLAG% = FALSE%: MAX.TIME% = 1: STROFF = 0: STROFF% = 0: DSPTR = 0
11880 MY.ADDR% = VAL(FLDS(1)) 'GET MY.ADDR%
11900 BD.ADDR% = VAL(FLDS(2)) 'GET BD.ADDR%
11920 PORT0% = BD.ADDR%: PORT1% = BD.ADDR% + 1: PORT2% = BD.ADDR% + 2: PORT3% = BD.ADDR% + 3:
PORT4% = BD.ADDR% + 4: PORT5% = BD.ADDR% + 5: PORT6% = BD.ADDR% + 6: PORT7% = BD.ADDR% + 7: PORT8%
= BD.ADDR% + 8: PORT9% = BD.ADDR% + 9
11940 CHAR$ = LEFT$(FLDS(3), 1)
11960 IF CHAR$ = "P" THEN TCIMODE% = 1: GOTO 12200
11980 IF CHAR$ <> "T" THEN 12080
12000 TCIMODE% = 2 'USER SPECIFIED WAIT AFTER 8292 COMM
12020 MS% = VAL(MID$(FLDS(3), 3, LEN(FLDS(3)) - 2))
12040 IF MS% = 0 THEN MS% = 5 'DEFAULT TO 5 MS
12060 GOTO 12200
12080 IF CHAR$ <> "I" THEN 12900
12100 TCIMODE% = 3 'TCI INTERRUPT
12120 INTR% = VAL(MID$(FLDS(3), 3, LEN(FLDS(3)) - 2))
12140 IF (INTR% < 2) OR (INTR% > 7) THEN 12900
12160 INTVECTOR% = (INTR% + 8) * 4: INTENABLE% = 2 ^ (INTR% - 2)
12180 INTMASK% = 255 - (2 ^ INTR%)
12200 SUBLIB% = &H72F: TIMEOUT% = &H80B: INTSETUP% = &H821: POLLBYTE% = &H451
12220 WRSTR% = &H92D: WRFIL% = &H9BD: CB.FLAG% = &H429: HCSR% = &H427: VCSR% = &H428
12240 RDSTR% = &HB11: RDFIL% = &HBFA
12260 DEF SEG = 0
'12280 CSEG = (256 * PEEK((&HF1 * 4) + 3)) + PEEK((&HF1 * 4) + 2)
12300 REM
12320 DEF SEG
12330 SAVESTAT% = INP(PORT0%) 'CLEAR IBF; SEE PG. 92
12340 IF (INP(PORT9%) AND 2) = 2 THEN 12340 'WAIT FOR 8292 IBF LOW
12360 OUT (PORT9%), &HF2 'RESET 8292
12380 OUT (PORT5%), 2 'RESET 8291A
12400 OUT (PORT5%), &H25 'INIT T1 DELAY
12420 OUT (PORT1%), &H93 '8291A INTR ENBLE 1
12440 OUT (PORT2%), 0 '8291A INTR ENBLE 2
12460 OUT (PORT3%), 0 '8291A SERIAL POLL MODE
12480 OUT (PORT5%), &H80 '8291A AUX MODE A
12500 OUT (PORT5%), &HA1 '8291A AUX MODE B, ENBLE CPT
12520 OUT (PORT6%), MY.ADDR% '8291A ADDR MODE
12540 OUT (PORT6%), &HE0 'DISABLE ADDR 1
12560 IF (INP(PORT9%) AND 2) = 2 THEN 12560 'WAIT FOR 8292 IBF LOW
12580 OUT (PORT8%), 0 'CLR 8292 ERR MASK
12600 IF (INP(PORT9%) AND 2) = 2 THEN 12600 'WAIT FOR 8292 IBF LOW
12620 OUT (PORT8%), &HA0 'ENABLE TCI
12640 COMM% = &HE6 'READ 8292 CONT STATUS REG
12660 GOSUB 23540 'ROUTINE TO WAIT FOR TCI
12680 IF (INP(PORT9%) AND 1) = 0 THEN 12680
12700 SYC% = INP(PORT8%) AND 8
12720 IF SYC% = 8 THEN CNTRLR% = TRUE% ELSE CNTRLR% = FALSE%
12740 DUMMY$ = SPACE$(255)
12760 IF CNTRLR% = FALSE% THEN 12840
12780 OUT (PORT4%), &H80
12800 OUT (PORT5%), 0
12820 RETURN
12840 OUT (PORT4%), 1 'ADDR MODE 1
12860 OUT (PORT5%), 0 'PON TO 8191A
12880 RETURN '8292 IN IDLE STATE
12900 PRINT "UNEXPECTED CHARACTER IN PARAM$...FUNCTION ABORTED"

```

```

12920 RETURN
13180 REM
13200 REM ***** READ SET-UP *****
13220 REM
13240 NEOS% = VAL(FLD$(2)); IF NEOS% = 0 THEN NEOS% = 13
13260 IF FLD$(3) = "EOI" OR FLD$(3) = "" THEN TERM% = 1: GOTO 13320
13280 IF FLD$(3) = "EOS" THEN TERM% = 2: GOTO 13320
13300 GOTO 23960 'BAD PARAMETER
13320 OUT PORT7%, NEOS%
13340 IF TERM% = 1 THEN N1% = &H82 ELSE N1% = &H86
13360 OUT PORT5%, N1% 'ENABLE HLD OFF ON END
13380 IF MY.FLAG% = TRUE% THEN 13500
13400 IF CNTRLR% = TRUE% THEN 13460
13420 IF (INP(PORT4%) AND 4) = 0 THEN 13420
13440 RETURN
13460 GOSUB 22780
13480 OUT PORT0%, &H3F 'UNL
13500 FUM% = 1: GOSUB 22420 'OUTPUT TALK ADDR
13520 GOSUB 22780
13540 OUT PORT0%, MY.ADDR% + &H20 'OUTPUT MLA FOR COMPLETENESS
13560 GOSUB 22780 'WAIT TILL RECEIVED
13580 OUT PORT4%, &H40 'LON MODE
13600 OUT PORT5%, 0 'PON TO 8291A
13620 COMM% = &HF6: GOTO 23540 'GTSB
13640 REM
13660 REM ***** READ END ROUTINE *****
13680 IF CNTRLR% = TRUE% THEN 13900
13800 OUT PORT5%, &H80 'CLR END COND
13820 LAST.INT1% = INT1STAT%
13840 OUT PORT5%, 3 'FN SH HS
13860 N1% = INP(PORT0%) 'CLEAR INPUT PORT
13880 RETURN
13900 COMM% = &HFD: GOSUB 23540 'TAKE SYNC CONT
13920 OUT PORT4%, &H80 'TON
13940 OUT PORT5%, 3 'FN SH HS
13960 OUT PORT5%, &H80 'CLR END COND
13980 OUT PORT5%, 0 'PON
14000 RETURN
14020 REM
14040 REM ***** RD.STR *****
14060 IEEE.FCTN$ = "RD.STR"
14080 GOSUB 13240 'READ SET-UP
14100 CTR% = 1: DATA.STRING$ = ""
14120 INT1STAT% = INP(PORT1%)
14140 IF (INT1STAT% AND 1) = 0 THEN 14200
14160 DATA.STRING$ = DATA.STRING$ + CHR$(INP(PORT0%))
14180 CTR% = CTR% + 1
14200 IF (INT1STAT% AND &H10) = &H10 THEN 13680 'GOTO END ROUTINE
14220 IF CTR% <= 255 THEN 14120
14240 PRINT: PRINT "Count overflow...data bytes received after DATA.STRING$ full: (hex)"
14260 PRINT
14280 INT1STAT% = INP(PORT1%)
14300 IF (INT1STAT% AND 1) = 0 THEN 14380
14320 CHAR% = INP(PORT0%)
14340 IF CHAR% < 16 THEN PRINT "0";
14360 PRINT HEX$(CHAR%); " ";
14380 IF (INT1STAT% AND &H10) = &H10 THEN 13680 'GOTO END ROUTINE
14400 GOTO 14280
14420 REM
14440 REM
14460 REM
14480 REM
14500 REM
14520 REM
14540 REM
14560 REM
14580 REM
14600 REM
14620 REM
14640 REM
14660 REM
14680 REM
14700 REM ***** RD.TO.FILE *****
14720 REM
14740 REM
14760 REM
14780 REM
14800 IEEE.FCTN$ = "RD.TO.FILE"
14820 OPEN FLD$(4) FOR OUTPUT AS #1
14840 GOSUB 13240 'READ SET-UP
14860 INT1STAT% = INP(PORT1%)
14880 IF (INT1STAT% AND 1) = 0 THEN 14920
14900 PRINT #1, CHR$(INP(PORT0%));
14920 IF (INT1STAT% AND &H10) = 0 THEN 14860
14940 CLOSE #1
14960 GOTO 13680 'GOTO END ROUTINE
14980 REM
15000 REM
15020 REM
15040 REM
15060 REM
15080 REM
15100 REM
15120 REM
15140 REM
15160 REM
15180 REM
15200 REM ***** WR.STR *****
15220 REM
15240 REM
15260 REM
15280 IEEE.FCTN$ = "WR.STR"
15300 REM
15320 GOSUB 16100 'WRITE SET-UP
15340 FOR CTR% = 1 TO LEN(DATA.STRING$) - 1

```



```

15360 CHAR$ = MID$(DATA.STRING$, CTR%, 1)
15380 OUT PORT0%, ASC(CHAR$)
15400 GOSUB 22780 'WAIT TILL CHAR IS RECEIVED
15420 NEXT
15440 CHAR% = ASC(MID$(DATA.STRING$, LEN(DATA.STRING$), 1)) 'GET LAST CHAR
15460 ON TERM% GOTO 15500, 15580
15480 REM *** SEND EOI ***
15500 OUT PORT5%, 6 'SEND EOI WITH THIS CHAR
15520 OUT PORT0%, CHAR%
15540 GOTO 15660 'JUMP TO END OF ROUTINE
15560 REM *** SEND EOS ***
15580 IF CHAR% = NEOS% THEN 15640 'DO NOT SEND TWO EOS
15600 OUT PORT0%, CHAR%
15620 GOSUB 22780
15640 OUT PORT0%, NEOS% 'SEND EOS
15660 LAST.INT1% = INT1STAT%
15680 IF CNTRLR% = FALSE% THEN RETURN
15700 COMM% = &HFD: GOTO 23540 'TAKE SYN CONTROL
15720 REM
16080 REM ***** WRITE SET-UP *****
16100 NEOS% = VAL(FLD$(2)): IF NEOS% = 0 THEN NEOS% = 13
16120 IF FLD$(3) = "EOI" OR FLD$(3) = "" THEN TERM% = 1: GOTO 16180
16140 IF FLD$(3) = "EOS" THEN TERM% = 2: GOTO 16180
16160 GOTO 23960 'BAD PARAMETER
16180 IF CNTRLR% = TRUE% THEN 16280
16200 IF (INP(PORT4%) AND 2) = 0 THEN 16200 'WAIT TILL ADDRESSED
16220 IF (LAST.INT1% AND 2) = 2 THEN 16260
16240 GOSUB 22780
16260 RETURN
16280 GOSUB 22780
16300 OUT PORT0%, MY.ADDR% + &H40 'MY TALK ADDR
16320 GOSUB 22780
16340 OUT PORT0%, &H3F 'UNLISTEN
16360 FUM% = 1
16380 GOSUB 21800 'OUTPUT DEVICE LISTEN LIST
16400 GOSUB 22780
16420 COMM% = &HFD: GOTO 23540 'GTSB
21480 REM
21500 REM *****
21520 REM PARSE PARAM$ INTO FIELDS
21540 REM
21560 x% = 0 'CLEAN COUNTER
21580 FOR N1% = 1 TO LEN(PARAM$)
21600 N2% = INSTR(N1%, PARAM$, "/") 'POSITION OF NEXT "/"
21620 FLD$(x%) = MID$(PARAM$, N1%, N2% - N1%)
21640 x% = x% + 1: N1% = N2%
21660 NEXT
21680 FLD$(x%) = "DONE"
21700 RETURN
21720 REM *****
21740 REM
21760 REM FETCH LISTEN ADDRESSES AND OUTPUT AS LISTEN ONLY
21780 REM
21800 y% = 1: N1% = 1: N2% = INSTR(FLD$(FUM%), ",")
21820 MY.FLAG% = FALSE%
21840 WHILE N2% <> 0
21860 REC$(y%) = MID$(FLD$(FUM%), N1%, N2% - N1%)
21880 y% = y% + 1: N1% = N2% + 1: N2% = INSTR(N1%, FLD$(FUM%), ",")
21900 WEND
21920 REC$(y%) = RIGHT$(FLD$(FUM%), (LEN(FLD$(FUM%)) + 1) - N1%)
21940 FOR CTR% = 1 TO y%
21960 N2% = INSTR(1, REC$(CTR%), ".")
21980 IF N2% = 0 THEN 22240 'NO SCG
22000 GOSUB 22780
22020 OUT (PORT0%), VAL(LEFT$(REC$(CTR%), N2% - 1)) + &H20
22040 N1% = N2% + 1
22060 N2% = INSTR(N1%, REC$(CTR%), ".")
22080 WHILE N2% <> 0
22100 GOSUB 22780
22120 OUT (PORT0%), VAL(MID$(REC$(CTR%), N1%, N2% - N1%)) + &H0
22140 N1% = N2% + 1: N2% = INSTR(N1%, REC$(CTR%), ".")
22160 WEND
22180 GOSUB 22780
22200 OUT (PORT0%), VAL(RIGHT$(REC$(CTR%), (LEN(REC$(CTR%)) + 1) - N1%)) + &H60
22220 GOTO 22300
22240 IF VAL(REC$(CTR%)) = MY.ADDR% THEN MY.FLAG% = TRUE%: GOTO 22300
22260 GOSUB 22780
22280 OUT (PORT0%), VAL(REC$(CTR%)) + &H20

```

```

22300 NEXT
22320 RETURN
22340 REM
22360 REM *****
22380 REM EXTRACT TALK ADDRESS AND OUTPUT
22400 REM FIELD # PASSED AS FUM#
22420 N2# = INSTR(1, FLDS(FUM#), ".")
22440 IF N2# = 0 THEN 22700 'NO SCG
22460 GOSUB 22780
22480 OUT (PORT0#), VAL(LEFT$(FLDS(FUM#), N2# - 1)) + &H40
22500 N1# = N2# + 1
22520 N2# = INSTR(N1#, FLDS(FUM#), ".")
22540 WHILE N2# <> 0
22560 GOSUB 22780
22580 OUT (PORT0#), VAL(MID$(FLDS(FUM#), N1#, N2# - N1#)) + &H60
22600 N1# = N2# + 1: N2# = INSTR(N1#, FLDS(FUM#), ".")
22620 WEND
22640 GOSUB 22780
22660 OUT (PORT0#), VAL(RIGHT$(FLDS(FUM#), (LEN(FLDS(FUM#)) + 1) - N1#)) + &H60
22680 RETURN
22700 GOSUB 22780
22720 OUT (PORT0#), VAL(FLDS(FUM#)) + &H40
22740 RETURN
22760 REM *****
22780 INP1STAT# = INP(PORT1#) 'READ INTERRUPT STATUS REGISTER 1
22800 IF (INP1STAT# AND 2) = 2 THEN RETURN ELSE 22780
23520 REM ***** 8292 COMMAND, WAIT FOR TCI *****
23540 IF (INP(PORT9#) AND 2) = 2 THEN 23540 'WAIT FOR INP BUFFER CLEARED
23560 ON TCIMODE# GOTO 23600, 23700, 23820 'WAIT FOR TCI
23580 REM TCIMODE# = 1...POLL# (REV C BOARD + LATER)
23600 OUT (BD.ADDR# + 10), 0
23620 OUT (PORT9#), COMM#
23640 IF (INP(BD.ADDR# + 12) AND 1) = 0 THEN 23640 ELSE RETURN 'WAIT FOR TCI
23680 REM TCIMODE# = 2...TIMED
23700 OUT (PORT9#), COMM#
23720 DEF SEG = CSEG
23740 'CALL SUBLIB# (MS#, TIMEOUT#)
23760 DEF SEG : RETURN
23800 REM TCIMODE# = 3...INTERRUPT
23820 DEF SEG = CSEG: POKE POLLBYTE#, 0 'CLEAR POLLBYTE#
23840 DEF SEG = CSEG: POKE POLLBYTE#, 0 'CLEAR POLLBYTE#
23860 'CALL SUBLIB# (BD.ADDR#, INTENABLE#, INTVECTOR#, INTMASK#, INTSETUP#)
23880 OUT (PORT9#), COMM#
23900 IF PEEK(POLLBYTE#) <> &HFF THEN 23900 'WAIT FOR POLLBYTE = &HFF
23920 DEF SEG : RETURN
23960 PRINT "Bad parameter in PARAM$; execution terminated."
23980 PRINT PARAM$: END

REM $STATIC
SUB censtr (row, strg$) STATIC
strg$ = LTRIM$(strg$): strg$ = RTRIM$(strg$): length = LEN(strg$)
col = 40 - length / 2: LOCATE row, col: PRINT strg$;
END SUB

SUB plot (x(), y(), np)
SCREEN pg#: CLS : VIEW
IF ngraph = 0 THEN
  IF pg# = 2 THEN
    xrange = 630 - 30 + 1: yrange = 195 - 5 + 1
    size = INT(xrange / 8 + 1) * yrange * CB# / 2 + 4: REDIM gst$(size)
  ELSEIF pg# = 9 THEN
    xrange = 630 - 30 + 1: yrange = 300 - 100 + 1
    size = INT(xrange / 8 + 1) * yrange * CB# + 4: REDIM gst$(size)
  ELSE
    xrange = 700 - 30 + 1: yrange = 330 - 5 + 1
    size = INT(xrange / 8 + 1) * yrange * CB# / 2 + 4: REDIM gst$(size)
  END IF
END IF
IF pg# = 2 THEN VIEW (130, 12)-(532, 148)
IF pg# = 9 THEN VIEW (130, 70)-(532, 220)
IF pg# = 3 THEN VIEW (143, 20)-(605, 258)
IF overlay$ = "1" AND gcode$ = "0" THEN
WINDOW: VIEW
IF pg# = 2 THEN PUT (30, 5), gst#
IF pg# = 9 THEN PUT (30, 50), gst#
IF pg# = 3 THEN PUT (30, 5), gst#
nolay# = nolay# + 1
IF pg# = 2 THEN VIEW (130, 12)-(532, 148)

```

```

IF pg% = 9 THEN VIEW (130, 70)-(532, 220)
IF pg% = 3 THEN VIEW (143, 20)-(605, 258)
GOTO dnp
ELSE
CLS
END IF
WINDOW (0, 0)-(500, 500): LINE (0, 0)-(500, 500), , B
FOR i = 1 TO 5
  FOR jy% = 0 TO 500 STEP 14: PSET (i * 100, jy%): NEXT jy%
  FOR jx% = 1 TO 500 STEP 10: PSET (jx%, i * 100): NEXT jx%
NEXT i
IF pg% = 9 THEN
LOCATE 15, 11: PRINT ymin: LOCATE 6, 11: PRINT ymax
LOCATE 18, 16: PRINT xmin: LOCATE 18, 66: PRINT xmax
ELSE
LOCATE 19, 11: PRINT ymin: LOCATE 2, 11: PRINT ymax
LOCATE 21, 16: PRINT xmin: LOCATE 21, 66: PRINT xmax
END IF
dnp: PSET (0, 0)
WINDOW (xmin, ymin)-(xmax, ymax)
FOR j% = 1 TO np
  IF sb% = 5 THEN
LINE -(x(j%), y(j%))
  ELSE
PSET (x(j%), y(j%)): DRAW SBOL$(sb%)
  END IF
NEXT j%
CALL windbox(50, 20, 950, 120)
lp1: LOCATE 22, 11: INPUT "Press (F) to overlay best fit curve or (C) to continue.. ", aa$
aa$ = UCASE$(aa$)
IF NOT (aa$ = "F" OR aa$ = "C") THEN GOTO lp1
LINE (50, 20)-(950, 120), 0, BF: PUT (50, 20), gst1%
IF aa$ = "F" THEN
  IF cflag$ = "0" THEN
CALL windbox(100, 100, 900, 200)
strg$ = "No best fit curves available, Go back and Run 'Curve-fit': CALL censtr(17, strg$)
strg$ = "Press 'ENTER' to go back ..": CALL censtr(18, strg$)
  ls5: IF INKEY$ <> CHR$(13) THEN GOTO ls5
  LINE (100, 100)-(900, 200), 0, BF: PUT (100, 100), gst1%
  ELSE
GOSUB fbfit
  END IF
END IF
WINDOW: VIEW
IF pg% = 2 THEN GET (30, 5)-(630, 195), gst%
IF pg% = 9 THEN GET (30, 50)-(630, 250), gst%
IF pg% = 3 THEN GET (30, 5)-(700, 330), gst%
overlay$ = "1": ngraph = ngraph + 1
IF gcode$ = "0" THEN ngraph = 1
CLS : GOTO esub
fbfit:
IF pg% = 2 THEN VIEW (130, 12)-(532, 148)
IF pg% = 9 THEN VIEW (130, 70)-(532, 220)
IF pg% = 3 THEN VIEW (143, 20)-(605, 258)
WINDOW (xmin, ymin)-(xmax, ymax)
sep = ABS((xmax - xmin) / 100): i = xmin
ls7: IF icc = 2 AND i = 0 THEN i = i + sep
IF i > xmax THEN GOTO ls6
ON icc GOTO ls8, ls9, ls10, ls11, ls12
ls8: sum = a + B * i: GOTO ppt
ls9: sum = a + B * LOG(i): GOTO ppt
ls10: sum = a + i ^ B: GOTO ppt
ls11: sum = a * EXP(B * i): GOTO ppt
ls12: sum = 0
FOR j% = 1 TO n: sum = sum + v(j%) * i ^ (j% - 1): NEXT j%
ppt: PSET (i, sum)
i = i + sep: GOTO ls7
ls6: RETURN
esub: END SUB

SUB ret13 (row, col) STATIC
strg$ = "Press ENTER to continue.."
IF col <> 0 THEN LOCATE row, col: PRINT SPACE$(75 - col)
IF col = 0 THEN CALL censtr(row, strg$) ELSE LOCATE row, col: PRINT strg$
LSP15: IF INKEY$ <> CHR$(13) THEN GOTO LSP15
END SUB

SUB windbox (px1, py1, px2, py2) STATIC

```

```

VIEW: WINDOW (0, 0)-(1000, 500)
pxr = px2 - px1 + 1: pyr = py2 - py1 + 1
REDIM gst1$(INT(pxr / 8 + 1) * pyr * CB% / 2 + 4)
GET (px1, py1)-(px2, py2), gst1%
LINE (px1, py1)-(px2, py2), 0, BF
LINE (px1, py1)-(px2, py2), , B
END SUB

```

```

/*      This program is used to display the following items of informations
        in graphical form.
        1. Rawdata.
        2. Frequency spectrum.
        3. Cepstrum.
        4. Amplitude distribution of the time signal.

        ++ assuming that all informations are stored on diskette.      */

#include "graphics.h"
#include "stdlib.h"
#include <string.h>
#include <math.h>
#include <stdio.h>
#include <errno.h>
#include <dos.h>
#include <dir.h>
#include <conio.h>
#include <alloc.h>
#include <io.h>
#include <fcntl.h>

void cplot(int n,float far *y,float a,float b);
int dplot(int n,float far *y,float a,float b);
int cursor(int n,float far *y,float a,float b,int element);
int readPRWdata(char *filename,int numb,int r,float far *x);

float far *x,far *y;
static float max,min;
main()
{
    FILE *in;
    char name1[45];
    char d[1];
    register int i;
    int n,nact,inv,c;
    float p,tmp;
    char t1[30],t2[30];
    if( (x=(float far *)farcalloc(16385,sizeof(float)))==NULL )
    {
        perror("memory error ");
        exit(1);
    }
    if( (y=(float far *)farcalloc(16385,sizeof(float)))==NULL )
    {
        perror("memory error ");
        exit(1);
    }

    AGAIN:
    c=menu_select();
    if(c==6)
    {
        farfree(x);
        farfree(y);
        exit(1);
    }
    if(c==5)
    {
        bw();
        goto AGAIN;
    }
    if(c==1 || c==2 || c==3) {
        printf("Enter series length : ");
        scanf("%d",&n);
    }
    printf("Filename : ");
    scanf("%s",t2);
    printf("Drive <a:/b:/c/> :");
    scanf("%s",t1);
    strcpy(name1, strcat(t1,t2));
    if(c==1)
    {
        /*      retrieve the time series      */
        printf("\n\n      Reading (in fast binary).....%s",name1);
        if(readPRWdata(name1,n/2048,5000,y)==-1)
        {

```

```

        printf("\nError in file %s \n",name1);
        goto loop2;
    }
    else
    {
        printf("\n\n      Reading.....");
        if((in=fopen(name1,"r"))==NULL){
            printf("Cannot open file %s \n",name1);
            goto loop2;
        }
        if(c==2 || c==3)
        {
            for (i=1;i<=n;++i)
            {
                nact=fscanf(in,"%f\n",&p);
                if(nact==EOF)
                {
                    printf("ERROR - out of data. File %s \n",name1);
                    goto loop2;
                }
                y[i]=p;
                x[i]=i;
            }
        }
        else if(c==4)
        {
            fscanf(in,"%f%d",&p,&n);
            for(i=1;i<=n;++i)
            {
                fscanf(in,"%f",&tmp);
                x[i]=tmp;
                fscanf(in,"%f",&tmp);
                y[i]=tmp;
                x[i]=x[i]-p;
            }
        }
        fclose(in);
    }
    printf("done \n");
    for(i=1;i<=n;++i)
    {
        if(c==1 || c==3 ) x[i]=i*1e-3;
        else if(c==2) x[i]=i*0.48828;
    }

    maxmin(n,y);
    cplot(n,y,x[1],x[n]);
loop2:
    goto AGAIN;
}

menu_select()
{
    char s[80];
    int c;
    printf("\n1. Rawdata ?\n");
    printf("\n2. Frequency spectrum ?\n");
    printf("\n3. Cepstrum ?\n");
    printf("\n4. Amplitude distribution ?\n");
    printf("\n5. Execute Bandwidth program ?\n");
    printf("\n6. Quit ?\n");
    do {
        printf("Enter selection (1-5) :");
        scanf("%s",s);
        c=atoi(s);
    }while(c<0||c>6);
    return c;
}

int readPRWdata(char *filename,int numb,int r,float far *x)
{
    float a1,b1,rd[2048];
    int i,j;
    int indata;
    unsigned int buffer[2048];
    a1=(3.05078125e-5)*r;
    switch (r)

```

```

{
    case 100:
        b1=-105.435+15.62;
        break;
    case 200:
        b1=-203.06+15.62;
        break;
    case 500:
        b1=-503.745+15.62;
        break;
    case 1000:
        b1=-991.87+15.62;
        break;
    case 2000:
        b1=-1983.74+15.62;
        break;
    case 5000:
        b1=-4920.3+15.62;
        break;
    case 10000:
        b1=-9762.5+15.62;
        break;
    default:
        printf("\nInvalid range");
        exit(1);
}
if( (indata=open(filename,O_BINARY|O_RDONLY))== -1 )
{
    perror("\ncan't open input file ");
    return -1;
}
for(i=0;i<numb;i++)
{
    if( lseek(indata,i*4130+32,SEEK_SET)==-1 )
    {
        perror("\ncan't position in the file properly ");
        return -1;
    }
    if( read(indata,buffer,4096)==-1 )
    {
        perror("\ncan't read from file ");
        return -1;
    }
    for(j=0;j<2048;j++)
    {
        x[i*2048+j+1]=buffer[j]*a1+b1;
    }
}
close(indata);
return 0;
}

maxmin(n,y)
int n;
float far *y;
{
    register int i;
    max=-99999;
    min=99999;
    for(i=1;i<=n;++i){
        if(y[i]>max) max=y[i];
        if(y[i]<min) min=y[i];
    }
    printf("%f %f\n",min,max);
    getch();
}

int gd;
int gm;
int lm;
int px,py,dx,dy,dw,dh,dd,th,d1;
int sex,sxx,sy,syx;

void cplot(int n,float far *y,float a,float b)
{
    detectgraph(&gd,&gm);
    getmoderange(gd,&lm,&gm);

```

```

    initgraph(&gd,&gm,"C:\\\\TC");
    setfillstyle(EMPTY_FILL,0);
    dx=0.2*getmaxx();
    dw=0.7*getmaxx();
    dy=0.05*getmaxy();
    dh=0.5*getmaxy();
    th=textheight("0");
    dd=dy+dh+4+th;
    sex=dx+dw/6;
    sy=dd+th+8;
    sxx=dx+dw/2;
    syx=dx+(5*dw)/6;
    dl=dd+2*th+22;
    dplot(n,y,a,b);
    closegraph();
}

int dplot(int n,float far *y,float a,float b)
{
    char NumBuf[20];
    int i;
    float pmax,nmax;
    int zl,zr,tmp;

    Start:
    pmax=y[1];
    nmax=y[1];
    cleardevice();
    for(i=2;i<=n;i++)
    {
        if (y[i]>pmax)
        {
            pmax=y[i];
        }
        if (y[i]<nmax)
        {
            nmax=y[i];
        }
    }
    rectangle(dx-1,dy-1,dx+dw+1,dy+dh+1);
    for(i=0;i<5;i++)
    {
        gcvt((b-a)*i/4+a,6,NumBuf);
        moveto(dx+dw*i/4,dy+dh);
        moverel(-textwidth(NumBuf)/2,4);
        outtext(NumBuf);
    }
    for(i=0;i<5;i++)
    {
        gcvt(nmax+(pmax-nmax)*i/4,6,NumBuf);
        moveto(dx,dy+(4-i)*dh/4);
        moverel(-textwidth(NumBuf)-6,-textheight(NumBuf)/2);
        outtext(NumBuf);
    }
    px=dx;
    py=dh*(pmax-y[1])/(pmax-nmax)+dy;
    moveto(px,py);
    for(i=2;i<=n;i++)
    {
        px=dx+dw*(1.0*(i-1))/(n-1);
        py=dh*(pmax-y[i])/(pmax-nmax)+dy;
        lineto(px,py);
    }
    rectangle(dx,dd+2,dx+dw,dd+2*th+8);
    moveto(sex-textwidth("element")/2,dd+4);
    outtext("element");
    moveto(sxx-textwidth("x-position")/2,dd+4);
    outtext("x-position");
    moveto(syx-textwidth("y-position")/2,dd+4);
    outtext("y-position");
    rectangle(dx,dl,dx+textwidth(" -cursor keys to move  -I to zoom in")+8,dl+4*th+2);
    moveto(dx+4,dl+1);
    outtext("press:");
    moveto(dx+4,dl+th+1);
    outtext(" -cursor keys to move  -I to zoom in");
    moveto(dx+4,dl+2*th+1);
    outtext(" -(1-6) to change speed  -0 to zoom out");
    moveto(dx+4,dl+3*th+1);

```



```

outtext(" -Q to quit");
zl=cursor(n,y,a,b,n/2);
if( zl>0 )
{
    zr=cursor(n,y,a,b,zl);
    if (zr<z1)
    {
        tmp=zr;
        zr=z1;
        z1=tmp;
    }
    if (zr==z1)
    {
        if(z1==n)
        {
            zr=z1-1;
        }
        else
        {
            zr=z1+1;
        }
    }
    if (dplot(zr-z1+1,y+z1-1,a+(b-a)*(z1-1)/(n-1),a+(b-a)*(zr-1)/(n-1))==0)
        goto Start;
}
if (z1==0)
    return 0;
else
    return 1;
}

int cursor(int n,float far *y,float a,float b,int element)
{
    char *scrnbuf,NumBuf[80];
    int pos,baseinc,inc,ch;
    size_t size;
    size=imagesize(1,dy,1,dy+dh);
    scrnbuf=(char *)malloc(size);
    baseinc=pow(1.0*n,1.0/5);
    inc=baseinc*baseinc;
    do
    {
        if( element==1 )
            pos=dx;
        else
            pos=((1.0*dw*(element-1))/(n-1)+dx);
        getimage(pos,dy,pos,dy+dh,scrnbuf);
        line(pos,dy,pos,dy+dh);
        bar(dx+1,dy+th+6,dx+dw-1,dy+2*th+7);
        gcvt(1.0*element,6,NumBuf);
        moveto(sxx-textwidth(NumBuf)/2,sy);
        outtext(NumBuf);
        gcvt((b-a)*(element-1)/(n-1)+a,6,NumBuf);
        moveto(sxx-textwidth(NumBuf)/2,sy);
        outtext(NumBuf);
        gcvt(y[element],6,NumBuf);
        moveto(syx-textwidth(NumBuf)/2,sy);
        outtext(NumBuf);
        ch=getch();
        if (ch==0)
        {
            ch=0x100+getch();
        }
        if ( (ch>='1') && (ch<='6') )
        {
            inc=pow(baseinc,1.0*(ch-'1'));
        }
        switch (ch)
        {
            case 'k':
            case 0x14D:
                element+=inc;
                if (element>n) element=n;
                break;
            case 'j':
            case 0x14B:
                element-=inc;
                if (element<1) element=1;

```

```

        break;
        case 'i':
        case 'I':
            free(scrnbuf);
            return element;
        case 'o':
        case 'O':
            free(scrnbuf);
            return 0;
        case 3 : /* Cntl-C */
        case 27 : /* Esc */
        case 'q':
        case 'Q':
            free(scrnbuf);
            return -1;
        default :
            ;
    }
    putimage(pos,dy,scrnbuf,0);
} while( 1 );
}
/*****
/*      B A N D W I D T H   P R O G R A M      */
/*
*****/

int get_str(char *buffer,int min,int max,char low,char hi);
void pause(int delay);
int yn(char *msg);

int bw()
{
    char name[13],names[200][13],nb[200][4],tmp[6];
    char spath[80],sourcefile[80],dpath[80],destfile[80];
    char drill[3],bwn[5],opt[2];
    int i,j,k,min,nfile,nholes,nbw,n;
    int bw[100][2];
    FILE *indata,*outdata;
    struct fblk fd;
    float temp,sum,for *Data;

    Data=y;

    FileData:

    spath[0]='\0';
    dpath[0]='\0';
    name[0]='\0';
    drill[0]='\0';
    bwn[0]='\0';

    printf("\n\nEnter source data path (eg. A:\\)\n ? ");
    get_str(spath,0,68,' ','~');
    printf("\nEnter destination data path (eg. B:\\)\n ? ");
    get_str(dpath,0,68,' ','~');

    printf("\n\nEnter drill number:");
    get_str(drill,2,3,'0','9');

    printf("\n\nEnter the number of frequencies:");
    tmp[0]='\0';
    get_str(tmp,1,5,'0','9');
    n=atoi(tmp);

    strcat(strcat(strcat(strcpy(sourcefile,spath),"D"),drill),"F");
    strcat(strcat(strcat(strcpy(destfile,dpath),"D"),drill),"B");
    strcpy(dpath,destfile);

    printf("\n\n Source files --> %sxx",sourcefile);
    printf("\n Destination file --> %sxx",destfile);
    printf("\n number of frequencies --> %d",n);

    if( yn("\n\nProceed") )
        goto FileData;

    BWData:

```

```

bwn[0]='\0';
printf("\n\nEnter the number of band width summations\n ? ");
get_str(bwn,1,2,'0','9');

printf("\nThe number of band width summations --> %s",bwn);

if( yn("\n\nIs this correct") )
    goto BWData;

nbw=atoi(bwn);

for(i=0;i<nbw;i++)
(
    printf("\n\nSummation #d",i+1);
    bwn[0]='\0';
    printf("\nEnter the file number (00-99) : ");
    get_str(bwn,2,3,'0','9');
    strcpy(nb[i],bwn);
    bwn[0]='\0';
    printf("\nEnter the lower band width number (1-%d) : ",n);
    get_str(bwn,1,5,'0','9');
    bw[i][0]=atoi(bwn)-1;
    bwn[0]='\0';
    printf("\nEnter the upper band width number (1-%d) : ",n);
    get_str(bwn,1,5,'0','9');
    bw[i][1]=atoi(bwn)-1;
)

ChangeData:
printf("\n\nSum #      lower      upper");
for(i=0;i<nbw;i++)
(
    printf("\n%d      %5d      %5d",i+1,bw[i][0]+1,bw[i][1]+1);
)

/* Prompt To See if Data Alright */
printf("\n\nEnter\n1) Proceed\n2) Change band width");
printf("\n3) Redo bandwidth\n4) Restart\n5) end program");
printf("\nOption : ");
opt[0]='\0';
get_str(opt,1,1,'1','5');
switch (opt[0])
(
    case '1' :
        break;
    case '2' :
        printf("\n\nEnter number to change : ");
        bwn[0]='\0';
        get_str(bwn,1,2,'0','9');
        i=atoi(bwn)-1;
        printf("\nEnter the file number (00-99) : ");
        get_str(bwn,2,2,'0','9');
        strcpy(nb[i],bwn);
        bwn[0]='\0';
        bwn[0]='\0';
        printf("\nEnter the lower band width number (1-%d) : ",n);
        get_str(bwn,1,5,'0','9');
        bw[i][0]=atoi(bwn)-1;
        bwn[0]='\0';
        printf("\nEnter the upper band width number (1-%d) : ",n);
        get_str(bwn,1,5,'0','9');
        bw[i][1]=atoi(bwn)-1;
        goto ChangeData;
    case '3' :
        goto BWData;
    case '4' :
        goto FileData;
    case '5' :
        return 0;
    default : ;
)

strcat(sourcefile,"*.");
printf("\n\nReading ... %s",sourcefile);

if( findfirst(sourcefile,&fd,0) )
(
    switch(errno)

```

```

        {
            case ENOFILE :
                printf("\nfft files not found");
                return 0;
            case ENOPATH :
                printf("\npath not found");
                return 0;
            default :
                perror("\nerror ");
                return -1;
        }
    }
    strcpy(names[0], fd.ff_name);
    nfile=1;
    while( !findnext(&fd) )
    {
        strcpy(names[nfile], fd.ff_name);
        nfile++;
    }
    if( _doserrno!=ENMFILE )
    {
        perror("\nerror ");
    }
    printf("\nSorting ... ");
    for(i=0; i<nfile-1; i++)
    {
        min=i;
        for(k=i+1; k<nfile; k++)
        {
            if( atoi(names[k]+4)<atoi(names[min]+4) )
            {
                min=k;
            }
        }
        strcpy(name, names[min]);
        strcpy(names[min], names[i]);
        strcpy(names[i], name);
    }
    for(i=0; i<nfile; i++)
    {
        printf("\n Found file ..... %s", names[i]);
    }

    for(k=0; k<nbw; k++)
    {
        sprintf(destfile, "%s%s", dpath, nb[k]);
        if( findfirst(destfile, &fd, 0) )
        {
            switch(errno)
            {
                case ENOFILE :
                case ENOPATH :
                    printf("\n\nCreating %s", destfile);
                    if( (outdata=fopen(destfile, "wt+"))==NULL )
                    {
                        perror("\ndestination file ");
                    }
                    if( fprintf(outdata, "%d %d\n", bw[k][0], bw[k][1])==EOF )
                    {
                        perror("\ndestination file ");
                    }
                    fclose(outdata);
                    break;
                default :
                    perror("\nerror ");
                    return -1;
            }
        }
        else
        {
            printf("\n\nAppending %s", destfile);
        }
    }

    for(i=0; i<nfile; i++)
    {
        strcpy(sourcefile, spath);
        strcat(sourcefile, names[i]);
    }

```

```

        printf("\n\nReading ... %s",sourcefile);
        if( (indata=fopen(sourcefile,"rt+"))==NULL )
        {
            perror("\nerror opening file ");
        }
        for(k=0;k<n;k++)
        {
            if( fscanf(indata,"%f\n",&temp)==0 )
            {
                perror("\nreading file\n");
                fclose(indata);
            }
            Data[k]=temp;
        }
        fclose(indata);
        for(k=0;k<nbw;k++)
        {
            sum=0.0;
            for(j=bw[k][0];j<bw[k][1];j++)
            {
                sum+=Data[j];
            }
            sprintf(destfile,"%s%s",dpath,nb[k]);
            if( (outdata=fopen(destfile,"at+"))==NULL )
            {
                perror("\ndestination file ");
            }
            printf("\n sum(%d-%d) = %g -> %s",bw[k][0]+1,bw[k][1]+1,sum,destfile);
            if( fprintf(outdata,"%s %g\n",names[i]+4,sum)==EOF )
            {
                perror("\ndestination file ");
            }
            fclose(outdata);
        }
        printf("\n\n");
        return 1;
    }

int get_str(char *buffer,int min,int max,char low,char hi)
{
    int l;
    char ch;
    while( kbhit() ) l=getch();
    l=strlen(buffer);
    printf(buffer);
    do
    {
        ch=(char)getch();
        if( ch==0 )
        {
            ch=(char)getch();
            ch=0;
        }
        if( (ch>=low) && (ch<=hi) && (l<max) )
        {
            putchar(ch);
            buffer[l]=ch;
            l++;
            continue;
        }
    } while(1);
    switch (ch)
    {
        case 3 :
            exit(-1);
            break;
        case 8 :
            if( l>0 )
            {
                l--;
                printf("\x08\x20\x08");
            }
            break;
        case 13 :
            if( l>=min )
            {
                buffer[l]='\0';
                return (l);
            }
    }
}

```

```

        }
        default :
        ;
    } while (l==1);
}

int yn(char *msg)
{
    char ch;
    printf("%s (Y/N) ? ",msg);
    do
    {
        ch=(char)getch();
        if( ch=='\x00' )
        {
            ch=(char)getch();
            ch=0;
        }
    } while ( (ch!='y') && (ch!='Y') && (ch!='n') && (ch!='N') );
    printf("%c",ch);
    if( (ch=='y') || (ch=='Y') )
    {
        return 0;
    }
    else
    {
        return 1;
    }
}

```

APPENDIX III

CURVEFIT OF DRILL LIFE EQUATION

To find the coefficients c and K of equation (42) using the least square curvefit program, the equation was linearized by taking the natural logarithm of both sides.

$$\ln T + \ln(V^2 * F)^c = \ln K$$

$$\text{let } Y = \ln T, X = \ln(V^2 * F), a = c \text{ and } b = \ln K.$$

$$\text{Then, } Y = -aX + b$$

Estimates of the constants a and b can best be done by the method of least squares. As part of this process, the error sum of squares, Z , is equated as:

$$Z = (Y + aX - b)^2 \quad (50)$$

To determine the minimum, the partial derivative of the error sum of squares with respect to each constant (a and b) is set equal to zero to yield

$$dZ/da = 2(Y + aX - b)X = 0$$

$$dZ/db = 2(Y + aX - b)(-1) = 0$$

Hence, the error sum of squares can be written as:

$$\sum XY + a \sum X^2 = b \sum X \quad (51)$$

$$\sum Y + a \sum X = nb, \quad (52)$$

where n is the number of data points.

Equations (51) and (52) are rearranged as follow:

$$\begin{bmatrix} \Sigma X - \Sigma X^2 \\ \Sigma X - n \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} \equiv \begin{bmatrix} - \Sigma XY \\ - \Sigma Y \end{bmatrix}$$

Therefore substituting $X_i = \ln V_i^2 * F_i$ and $Y_i = \ln T_i$ into the curvefit program, which is shown in Appendix I, we can obtain two arbitrary constants a and b. Also, since $c = a$ and $k = e^b$, we can obtain the constants c and k of the equation (42). With the execution of the above procedures, the drill life equation (42) was modified for the drilling conditions in this study as follows:

$$T * (V^2 * F)^{1.72} = 3508$$

APPENDIX IV

The general mathematical procedure to solve the third degree polynomial equation is described in this appendix.

The general equation of of AE count, ζ , in terms of drill life, h , is expressed as follow:

$$\alpha_1 * h^3 + \alpha_2 * h^2 + \alpha_3 * h + \beta_0 = 0 \quad (53)$$

where $\beta_0 = \alpha - \zeta$

Substitute $h = y - \alpha_2/3\alpha_1$ into equation 53, which then can be rewritten as:

$$y^3 - \left[\frac{\alpha_3}{\alpha_1} - \frac{\alpha_2^2}{3\alpha_1^2} \right] * y + \left[\frac{\beta_0}{\alpha_1} - \frac{\alpha_2 * \alpha_3}{3\alpha_1^2} + \frac{2\alpha_2^3}{27\alpha_1^3} \right] = 0$$

Reducing above equation to the form of

$$y^3 + p * y + q = 0 \quad (54)$$

where

$$p = \frac{\alpha_3}{\alpha_1} - \frac{\alpha_2^2}{3\alpha_1^2},$$

$$q = \frac{\beta_0}{\alpha_1} - \frac{\alpha_2 * \alpha_3}{3\alpha_1^2} + \frac{2\alpha_2^3}{27\alpha_1^3}$$

The solutions to equation (53) are

$$y_1 = \sqrt[3]{A} + \sqrt[3]{B} \quad (55)$$

$$y_2 = \omega \sqrt[3]{A} + \omega^2 \sqrt[3]{B} \quad (56)$$

$$y_3 = \omega^2 \sqrt[3]{A} + \omega \sqrt[3]{B} \quad (57)$$

where

$$A = -\frac{Q}{2} + \sqrt{\left(\frac{Q}{2}\right)^2 + \left(\frac{P}{3}\right)^3}$$

$$B = -\frac{Q}{2} - \sqrt{\left(\frac{Q}{2}\right)^2 + \left(\frac{P}{3}\right)^3}$$

and

$$\omega = \frac{-1 + i\sqrt{3}}{2}$$

Therefore, the general solutions of h in equation (53) with respect to ζ are obtained as follows:

$$h_1 = y_1 - \frac{\alpha_2}{3\alpha_1} \quad (58)$$

$$h_2 = y_2 - \frac{\alpha_2}{3\alpha_1} \quad , \quad \alpha, \beta = 0 \quad (59)$$

$$h_3 = y_3 - \frac{\alpha_2}{3\alpha_1} \quad (60)$$

Substituting the constants α , and removing imaginary numbers in results, the normalized drill life equation is derived as

$$h = y + 0.433 \quad (61)$$

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